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Solar Heating and Cooling of Buildings as a Contribution to Climate Change Abatement
-illustrated through a Case Study of Greece-

A Master's Thesis submitted for the degree of
"Master of Science"

supervised by
Dr. Ekkehart Naumann

Samar Elagabani

0226022

Vienna, 11 June 2012

Affidavit

I, **SAMAR ELAGABANI**, hereby declare

1. that I am the sole author of the present Master's Thesis, "SOLAR HEATING AND COOLING OF BUILDINGS AS A CONTRIBUTION TO CLIMATE CHANGE ABATEMENT -ILLUSTRATED THROUGH A CASE STUDY OF GREECE", 90 pages, bound, and that I have not used any source or tool other than those referenced or any other illicit aid or tool, and
2. that I have not prior to this date submitted this Master's Thesis as an examination paper in any form in Austria or abroad.

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Signature

Abstract

The essence of this master’s thesis is to contribute to research work on climate change abatement. It aims at providing a theoretical estimate of carbon dioxide (CO_2) saving potential in residential buildings if solar thermal energy technologies were to be applied for the supply of space heating and cooling. Illustrated by means of a case study of Greece, this paper presents current energy demand and supply with respect to space heating and cooling of dwellings, their respective CO_2 emission as well as a conclusion with the precise amount of prospective reduction of CO_2 discharge into the atmosphere when deploying solar thermal installations on 30% of dwelling units in the Greek residential sector. Further, basic economic considerations are taken into account.

Keywords: Climate Change Abatement; Energy Demand and Supply; Solar Thermal Collectors; Ad/absorption Chiller and Desiccant Cooling; Energy Sector Greece.

Acknowledgments and Dedication

It is with sincere gratitude that I acknowledge the guidance and constant support of my supervisor, Dr. Ekkehart Naumann. I, therefore, wish to take this opportunity to thank him, first and foremost, for his valuable assistance in structuring the research work as well as facilitating the realization and finalization of the thesis.

I would like to thank all Professors of the Diplomatic Academy of Vienna as well as the Vienna University of Technology for their stimulating lectures that have supported and complimented my endeavour throughout the two years of *Environmental Technology and International Affairs*.

Furthermore, it gives me great pleasure to express my gratitude to my dear parents, Zahrat and Fouad. Without their unconditional love and everlasting motivation, this thesis would have remained a dream.

Finally, I wish to express appreciation to my dearest one, my beloved husband, Monzir, who always stood by my side during these tough years with patience and understanding, but also enthusiastic support and encouragement.

Last but not least, I wish to dedicate this master’s thesis to my dearest baby boy Yousif, who now is two years old and has his whole life awaiting. However, I would like to take this great moment to advise him, as a mother and friend, that nothing great is achieved without effort and passion.

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1. Introduction

The subject of this master thesis was chosen in context of a Master of Science Programme of an interdisciplinary nature, namely *Environmental Technology and International Affairs*, a joint cooperation programme of the Diplomatic Academy of Vienna and the Vienna University of Technology. As the title reveals, global environmental issues are the focus, which means, in the course of this paper, the abatement of climate change, caused by global warming as a result anthropogenic greenhouse gas (GHG) emissions, from fossil fuel combustion. Environmentally sound technologies are used to reduce the negative impact on the ecology.

Precisely, the objective of this paper is to contribute research work towards facing the challenge of reducing carbon dioxide (CO_2) emission into the atmosphere in the context of a national energy mix, focusing on the South European country Greece.

The prime research question of this master's thesis is as follows: *Can Solar Cooling and Heating contribute to Climate Change Abatement?* The hypothesis states that replacement of the traditional energy source of fossil fuel combustion by solar energy in the housing sector can contribute significantly to carbon dioxide mitigation. Throughout this paper, data and information from different relevant disciplines (research on climate change, prime energy supply and demand, Greece's national sectoral patterns of energy mix of economic activities and respective emissions of greenhouse gases, basic economic considerations, technical processes for heating and cooling based on Renewable Energy Sources), are compiled and evaluated in order to attain a scientifically based background for verification or falsification of the hypothesis.

This paper faces a two-fold challenge; on the one hand, it discusses the current global issue of climate change, while, on the other hand, it aims to tackle this challenge by means of targeting the cooling and heating sector through the application of renewable solar energy, specifically the utilization of solar thermal energy. A technical excursion is undertaken to introduce the functionality of state of the art technologies of both solar thermal collectors and cooling devices deployed for solar heating and cooling.

The experimental part of this thesis is a case study of Greece, a climate favourable to the deployment of solar energy. To achieve an effective national change of reducing CO_2 emission, policy and relevant financing aiming at responding to the challenge become an issue, thus an insight into Greece's positive policy of promoting renewable energy sources in the residential sector is given. Research is done regarding Greece's energy sector as well as the consumption pattern observed, in order to further discuss CO_2 emissions and assess potential reduction possibilities. To conclude with facts and figures, the Greek building sector is put under the microscope to determine the amount of energy demanded by existing dwelling units. Obtaining this outcome then allows concluding with a potential amount of carbon dioxide reduction if solar heating and cooling is applied, thus stating the Greek building sector's contribution to climate change abatement.

2. Compilation and Evaluation of Scientific Research

2.1 Climate Change Discussion

Sound scientific evidence, provided by instrumental records since 1958, in addition to proxy data since 650.000 years before the present (as of 1950), confirm that today's extreme rise of atmospheric CO_2 emissions is of anthropogenic origin. Without doubt, viewing Figure 2.1.1, the Earth repeatedly experienced relative low as well as high CO_2 concentration cycles over time.

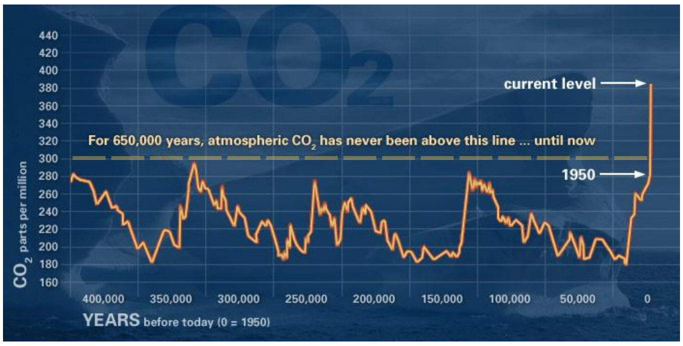


Figure 2.1.1: Global Climate Change: Carbon Dioxide Concentration over 650.000 Years
Source: National Aeronautics and Space Administration (NASA)

As can be seen from Figure 2.1.1, CO_2 levels have under no circumstances surpassed 300 ppm (parts per million), which one could define as the natural condition of the planet. Current (March 2012) atmospheric CO_2 concentration accounts to 394.45 ppm, rising annually (Mauna Loa Observatory: NOAA-ESRL, 2012). To put this in perspective, CO_2 concentration of March 2011 and March 2010 accounted to 392.40 ppm and 391.08 ppm respectively (Mauna Loa Observatory: NOAA-ESRL, 2012). As Earth came to existence, it contained atmospheric CO_2 concentrations way above our current level. With time and the start of photosynthesis, CO_2 concentration decreased while O_2 levels increased to the amount where life was possible. Thus, Earth survives high CO_2 concentrations. However, we human beings would find it extremely challenging to endure Earth's change of climatic conditions. "Warming of the climate system is unequivocal, as is now evident from observations of increases in global average air and ocean temperatures, widespread melting of snow and ice and rising global average sea level" (IPCC, 2007). Therefore, climate experts, such as Nicholas Stern, support an upper boundary of CO_2 concentration of 350 ppm

(Manford, 2009). Figure 2.1.2 illustrates the various parts of the world, comparing their carbon dioxide emissions. Figure 2.1.3 shows a flow chart of global greenhouse gas emissions of the year 2005.

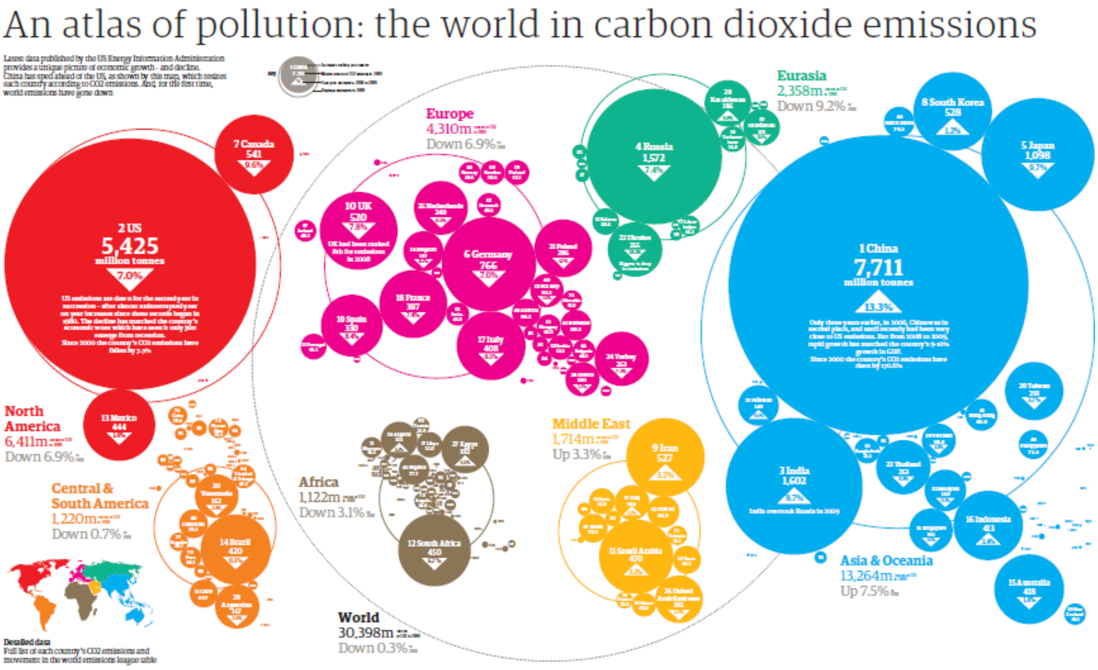


Figure 2.1.2: Carbon Web. An Atlas of Pollution: The World in Carbon Dioxide Emissions. From left to right, red: North America, orange: Central & South America, pink: Europe, green: Eurasia, brown: Africa, yellow: Middle East, and blue: Asia & Oceania
Source: The Guardian, 2011

As early as 1886, Arrhenius, a Swedish scientist, hypothesised the increase of global average temperature caused by carbon dioxide emission, but was, however, scientifically opposed by other scientists. Carbon dioxide is a naturally occurring greenhouse gas present in the upper atmosphere, and is the primary climate change factor due to its Global Warming Potential (GWP). CO_2 is emitted naturally through the carbon cycle (Figure 2.1.4) and through anthropogenic activities, primarily fossil fuel combustion and deforestation (IPCC, 2007).

Other main elements of the composition of naturally occurring greenhouse gases include water vapour (H_2O), methane (CH_4), and nitrous oxide (N_2O) (Jacob, 1999). Even though CH_4 has a GWP 21 times that of CO_2 (U.S. Environmental Protection Agency, 2010), it is CO_2, the chief portion of trace gases of atmospheric GHG that “is responsible for 60% of the enhanced ‘greenhouse effect’” (BBC Weather Centre, 2009).

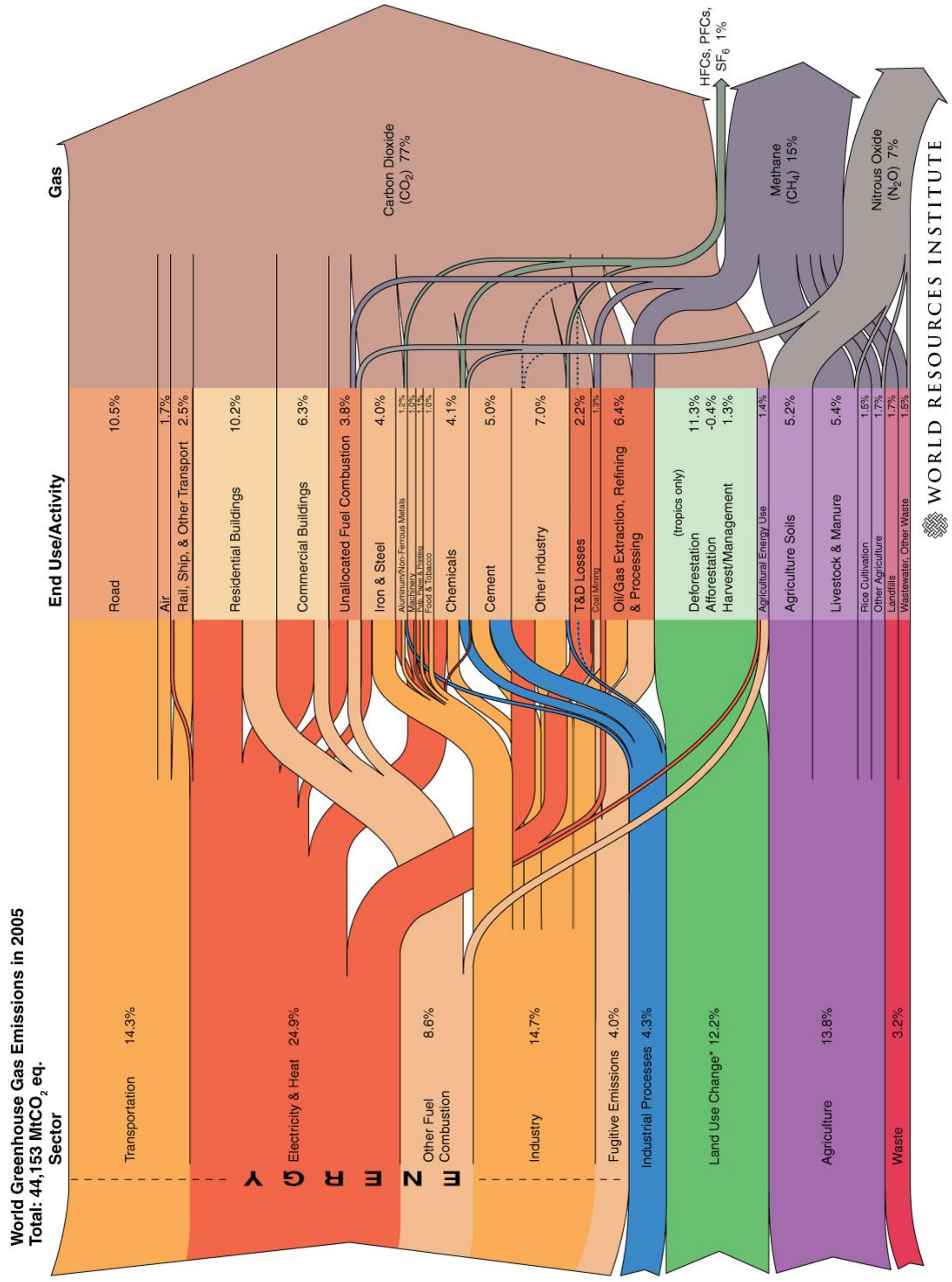


Figure 2.1.3: Flow Chart of Global Greenhouse Gas Emissions in 2005
Source: World Resources Institute, 2005

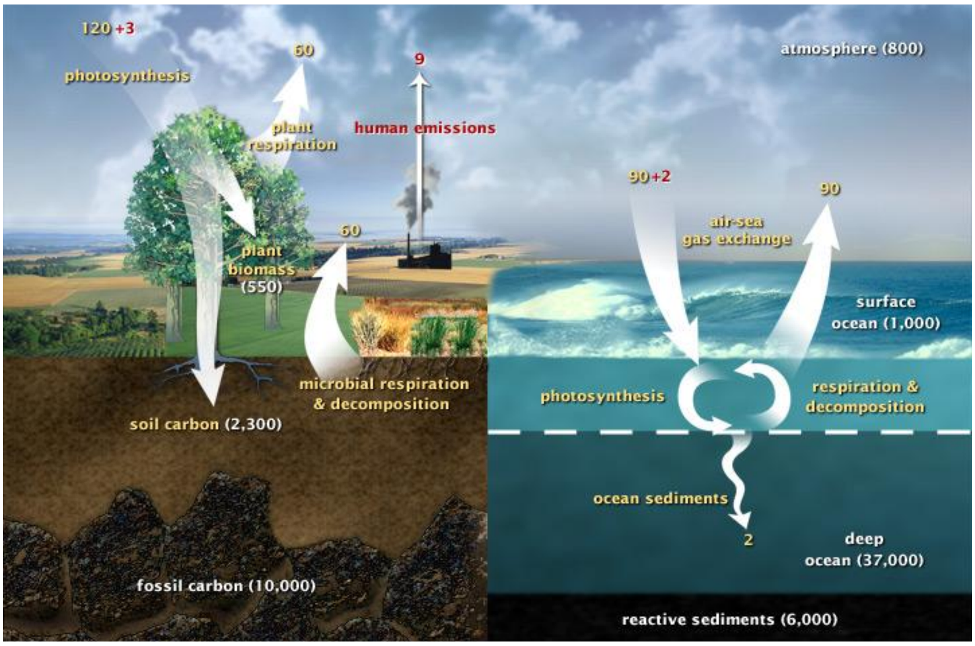


Figure 2.1.4: Fast Carbon Cycle: Movement of Carbon between Land, Atmosphere, and Oceans
Yellow: natural fluxes, red: anthropogenic contribution, and white: stored carbon (gigatons of carbon per year)
Source: NASA Earth Observatory, 2011

G.S. Callendar, an English engineer, expanded on the work of Arrhenius, contributing to the physics of anthropogenic CO_2 emissions trapping radiation, consequently increasing global temperature. He made his argument in 1938 and it became known as the ‘Callendar effect’, though misleadingly referred to as the greenhouse effect. His theory as well was dismissed, at that time, as false and implausible.

Two decades later, a few more researchers become conscious of the fact that Global Warming (average temperature increase) was in fact possible, thus, more was invested on climate research. In the 1960s, simple mathematical models such as the ‘Keeling Curve’ (Figure 2.1.5), named after the American scientist C.D. Keeling, were introduced, presenting precise recordings of atmospheric CO_2 concentration since 1958, demonstrating a constant increase. Not only has CO_2 concentration increased tremendously, also CH_4, N_2O and CFC-11 (an additional greenhouse gas caused by the chemical industry) have amplified over the past decades, as illustrated in Figure 2.1.6. Note the constant but slow increase of concentrations until the industrial revolution, while thereon an exponential growth is being experienced until today (2000).

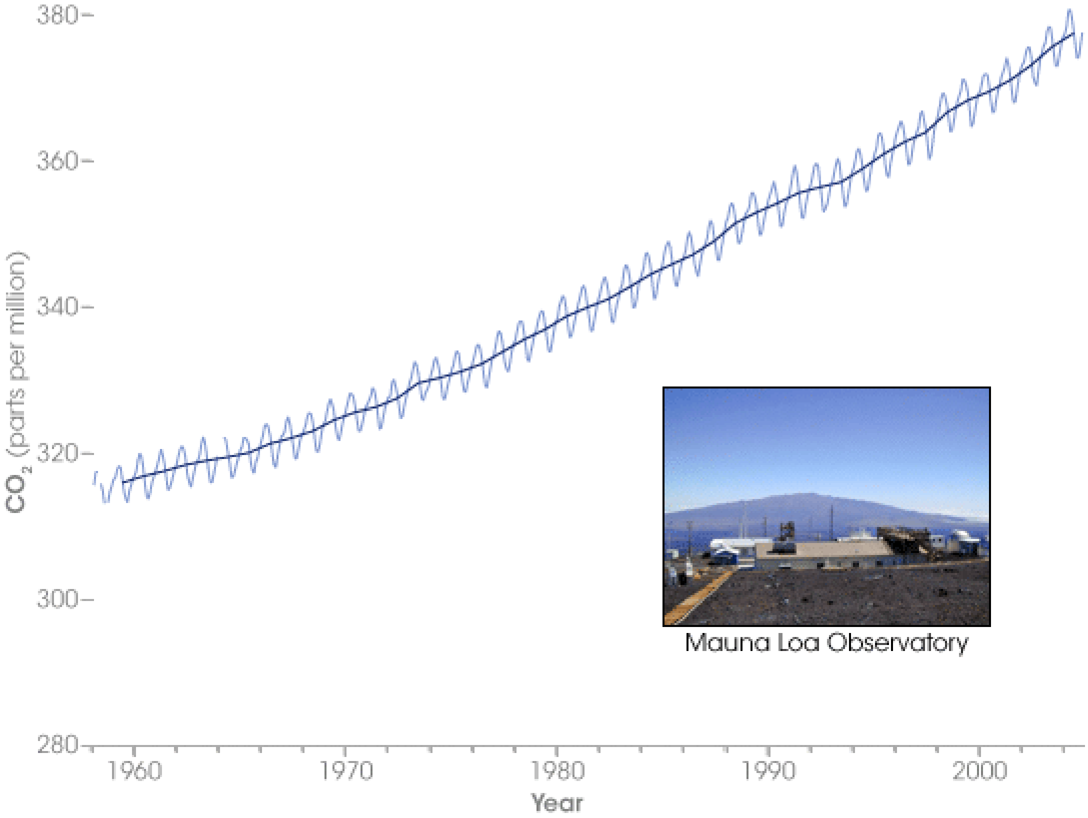


Figure 2.1.5: Keeling Curve
Source: NASA Earth Observatory, 2005

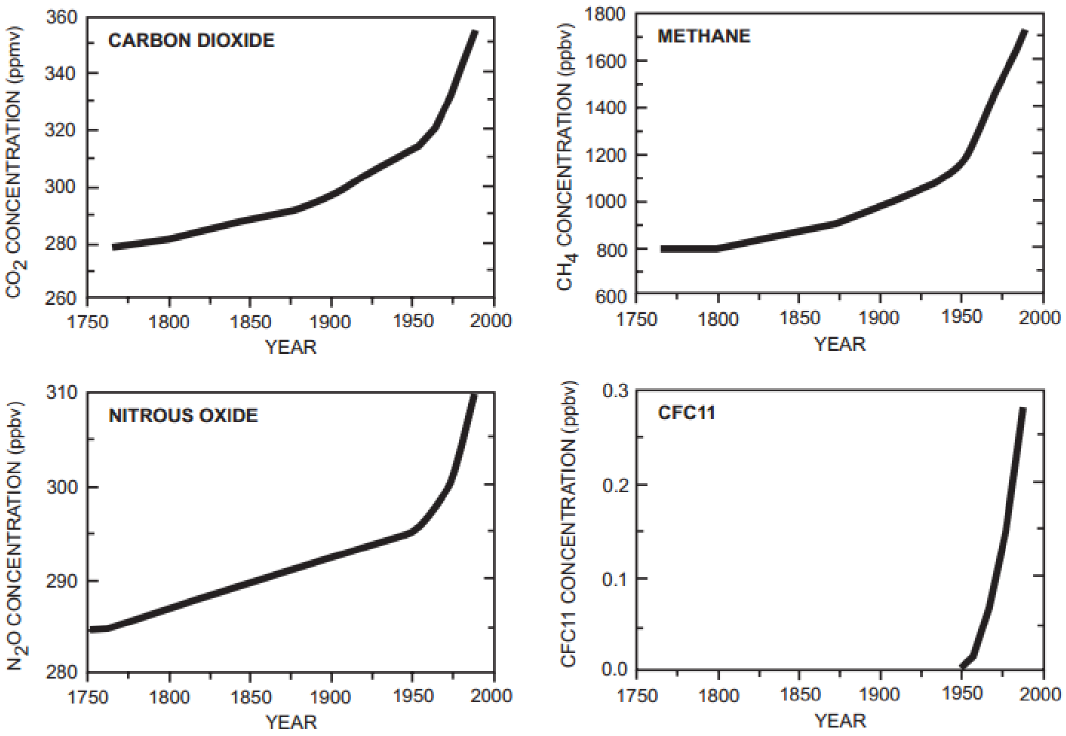


Figure 2.1.6: Increasing Concentrations of CO_2, CH_4, N_2O and CFC-11 since the 18th Century
Source: Jacob D., 1999

As of that time, when it was discovered that atmospheric gas plays a vital role in climate change and with the rise of environmentalism and public awareness, the international community took action by means of the 1979 First World Climate Conference. Identifying climate change as an urgent world problem, the World Climate Programme was set up. In the year 1988, the Intergovernmental Panel on Climate Change (IPCC) was established by United Nation General Assembly Resolution 43/53. It consisted of the World Meteorological Organization (WMO) and the United Nations Environment Program (UNEP). The IPCC is a scientific body entrusted "to provide the world with a clear scientific view on the current state of knowledge in climate change and its potential environmental and socio-economic impacts" (IPCC homepage).

The United Nations Framework Convention on Climate Change (UNFCCC), the first international treaty addressing Climate Change, was adopted at the United Nations Conference on Environment and Development (informally known as Rio Earth Summit) and entered into force in 1994, with Article 2, stating the ultimate objective as follows:

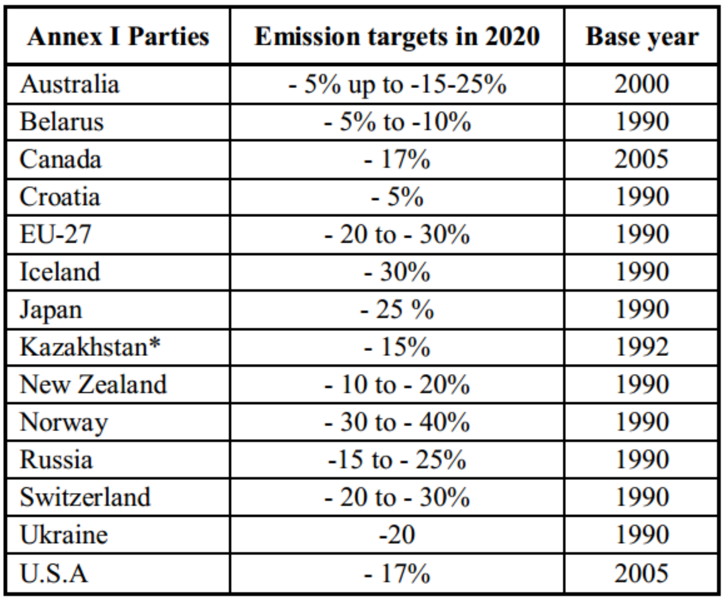
"The ultimate objective…is to achieve, in accordance with the relevant provisions of the Convention, stabilization of greenhouse gas concentrations in the atmosphere at a level that would prevent dangerous anthropogenic interference with the climate system…"

The Kyoto Protocol, a protocol to the UNFCCC adopted in 1997, entering into force in 2005, aimed at combating global warming, legally binding industrialized countries to reduce emissions of six main greenhouse gases, "of which carbon dioxide, mainly from burning of fossil fuels, is the most prevalent" (Fletcher and Parker, 2007). On average, five per cent of greenhouse gases against 1990 levels shall be reduced over a period of five years, 2008 until 2012 (UNFCCC homepage).

Since the UNFCCC's establishment, annual meetings of the Conference of the Parties take place, primarily to "assesses the effects of the measures taken by Parties and the progress made in achieving the ultimate objective of the Convention" (UNFCCC homepage). Since 2005, the annual meeting of the Conference of the Parties, serving as the meeting of the Parties to the Kyoto Protocol, takes place to review the “implementation of the Kyoto Protocol and takes decision to promote its effective implementation” (UNFCCC homepage).

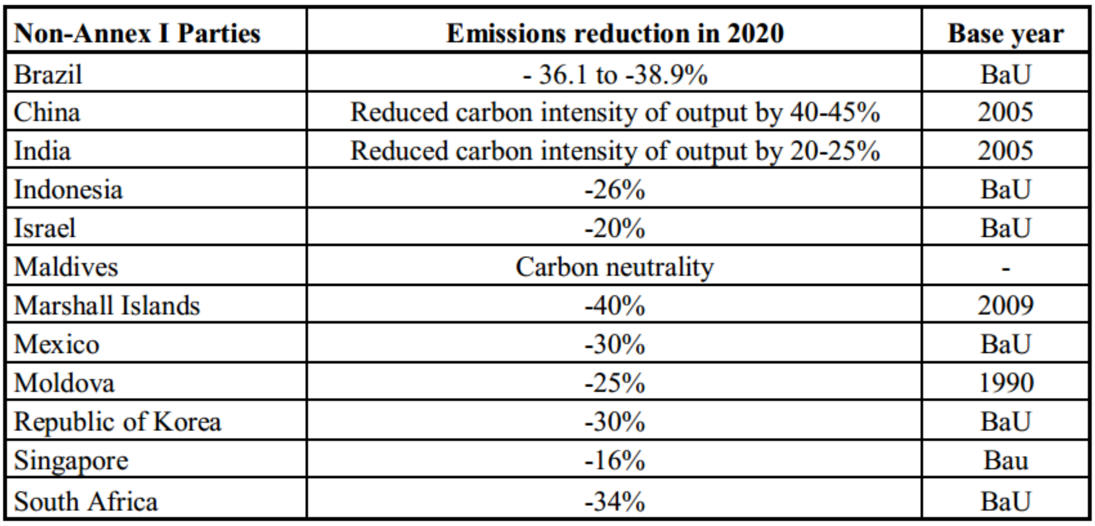
Today, however, global greenhouse gas emissions are still progressively accumulating, and the outcome of the most recent United Nations Climate Change Conference of 2011, which took place in Durban, South Africa, can be understood as having “reached at the last moment, to deny the new failure of the international diplomacy on climate change” (Mele, 2012). Tables 2.1.1 and 2.1.2 respectively illustrate pledges regarding emission reductions by Annex I as well as Non-Annex I countries. Nevertheless, to conclude, with or without individual active adaptation and mitigation measures aiming at reducing greenhouse gas emissions, climate change is a current actual occurrence and an inevitable global phenomenon, of which consequences include global mean air and ocean temperature rise, causing extensive ice and snow melting as well as rise in global average sea level (Fourth Assessment Report of the Intergovernmental Panel on Climate Change, 2007).

Table 2.1.1: Annex I Pledges
Source: Mele, 2012



Annex I Parties	Emission targets in 2020	Base year
Australia	- 5% up to -15-25%	2000
Belarus	- 5% to -10%	1990
Canada	- 17%	2005
Croatia	- 5%	1990
EU-27	- 20 to - 30%	1990
Iceland	- 30%	1990
Japan	- 25 %	1990
Kazakhstan*	- 15%	1992
New Zealand	- 10 to - 20%	1990
Norway	- 30 to - 40%	1990
Russia	-15 to - 25%	1990
Switzerland	- 20 to - 30%	1990
Ukraine	-20	1990
U.S.A	- 17%	2005

Table 2.1.2: Non-Annex I Quantified Pledges
Source: Mele, 2012



Non-Annex I Parties	Emissions reduction in 2020	Base year
Brazil	- 36.1 to -38.9%	BaU
China	Reduced carbon intensity of output by 40-45%	2005
India	Reduced carbon intensity of output by 20-25%	2005
Indonesia	-26%	BaU
Israel	-20%	BaU
Maldives	Carbon neutrality	-
Marshall Islands	-40%	2009
Mexico	-30%	BaU
Moldova	-25%	1990
Republic of Korea	-30%	BaU
Singapore	-16%	Bau
South Africa	-34%	BaU

2.2 Combating Climate Change

"I'd put my money on the sun and solar energy. What a source of power! I hope we don't have to wait until oil and coal run out before we tackle that."

Thomas Edison, 1931

On account of the radiative equilibrium between our Earth and the Sun, life on Earth can persist, unlike on our neighbouring planets Venus, which has an average surface temperature of 735 K (NASA, 2010), which is 464°C and Mars with an average surface temperature of 210 K (NASA, 2010), which is -63°C. The average global temperature of the Earth remains relatively stable and above freezing point. This allows Earth's special characteristic of liquid water, which is critical for any life to develop and continue.

Solar radiation travels towards the Earth with the speed of light and leaves the Earth's atmosphere with the same rate (Jacob, 1999). Thus, the more energy the Earth receives from the Sun, the more energy is emitted by the Earth (NASA National Aeronautics and Space Administration, 2011). This considerable phenomenon, called global energy balance, prevents overheating of the Earth and, in the long-run, maintains the Earth in a state of equilibrium (incoming energy equals outgoing energy), having a radiative temperature of 288K, i.e. 15°C (Jacob, 1999), which in fact, corresponds to the mean surface temperature.

The Earth’s atmosphere mainly consists of nitrogen (78%) and oxygen (21%), however, also trace gases (1%), also known as greenhouse gases (NOAA, 2011). The significant characteristics of greenhouse gases, which are relevant to the topic of climate change, are on the one hand their transmissivity of the Sun’s energy to the Earth’s surface, on the other hand, however, their ability to absorb the energy emitted by the Earth and further reemit a part back to the Earth’s surface (NOAA, 2011). This process traps the heat, resulting in a warming effect. Even though greenhouse gas aids the Earth in preserving a relatively stable mean temperature, which is comfortable for human life, the consequence of excess greenhouse gas is global warming, changing the global climate, leading to consequences which are threatening to human life on Earth. Indeed, regarding our current case, carbon dioxide accumulation of the concentration in the upper atmosphere today is higher than it has been since the last two million years (ScienceDaily, 2009). Moreover, this is a consequence of anthropogenic activities, primarily due to the combustion of fossil fuels (IPCC, 2007). Therefore, combating climate change is through either change in human behaviour (demand side management) or technical solutions eliminating CO_2 emission into the environment. This thesis is about the technical solution. Figure 2.2.1 illustrates the effect of excess greenhouse gas in the atmosphere, demonstrating the incoming shortwave radiation from the Sun being mainly absorbed by the Earth’s surface, whereas the emitted long-wave radiation by the Earth’s surface being trapped by clouds (representation of excess greenhouse gas), thus causing a warming effect.

Figure 2.2.1: Earth’s Incoming and Outgoing Radiation
Source: National Aeronautics and Space Administration, Science Mission Directorate, 2010

2.3 Energy and Greenhouse Gas Emission

Based on scientific models and calculations, current global warming is an authentic fact causing climate change on planet Earth, thus substantial mitigation actions have to take place today, to save our world tomorrow. Therefore, the objective of this paper is to contribute in research work to obtain sustainable, efficient and cost-effective technical solutions for climate change abatement in the building sector, by means of reducing CO_2 emission from buildings through the reduction of emission caused by human energy demand. According to Figures 2.3.1 and 2.2.2, in Europe as well as in the United States of America respectively, about 40% of final energy demand is due to services in commercial and residential buildings, making this a dominating energy requiring sector.

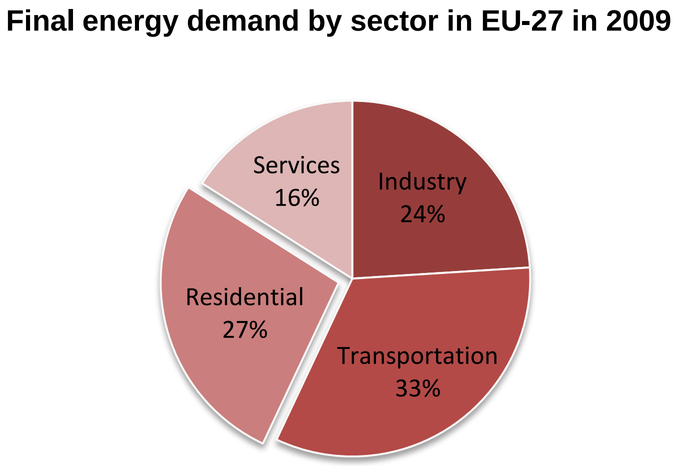


Figure 2.3.1: Final Energy Demand by Sector, EU-27, 2009
Source: Eurostat, 2009

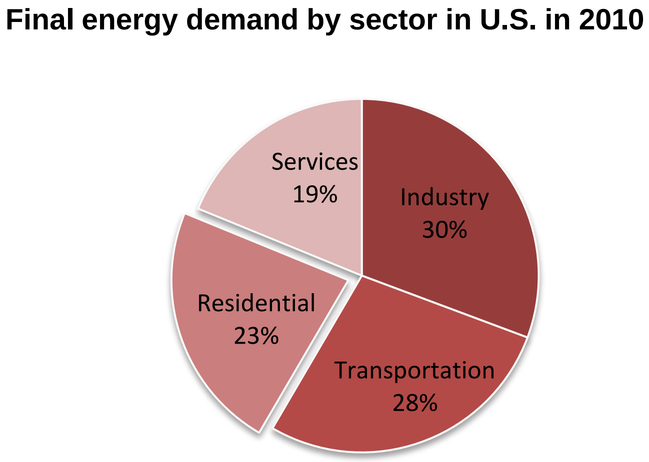


Figure 2.3.2: Final Energy Demand by Sector, United States of America, 2010
Source: U.S. Energy Information Administration, Annual Energy Review 2010

Zooming into the residential building sector, more than half of energy consumption is devoted to space heating/cooling and water heating, in both Europe and the United States (Figure 2.3.3 and 2.3.4). Searching for energy saving solutions in this section is thus, of utmost importance due to the potential of producing a great effect on global climate change abatement by means of sustainable reduction of greenhouse gas emissions, once heating and cooling is powered by a renewable and clean energy source.

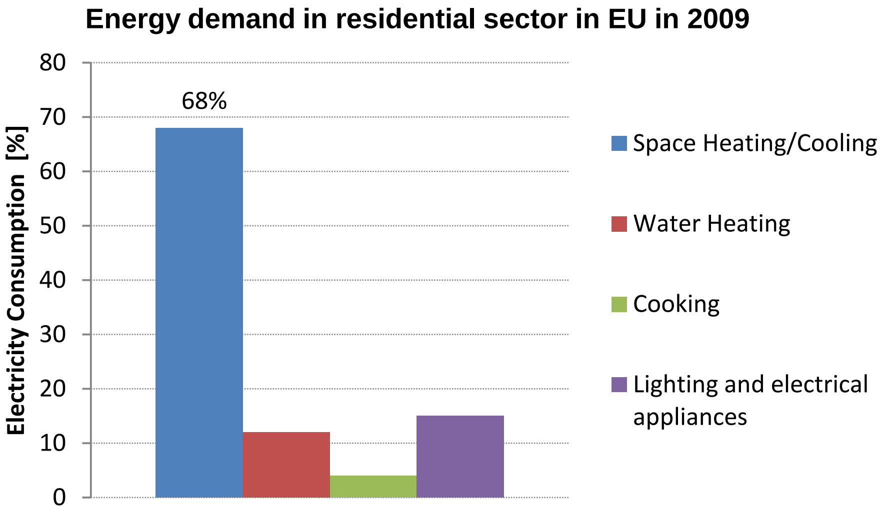


Figure 2.3.3: Energy Demand in the Residential Sector, EU, 2009
Source: Odyssee Indicators, 2009

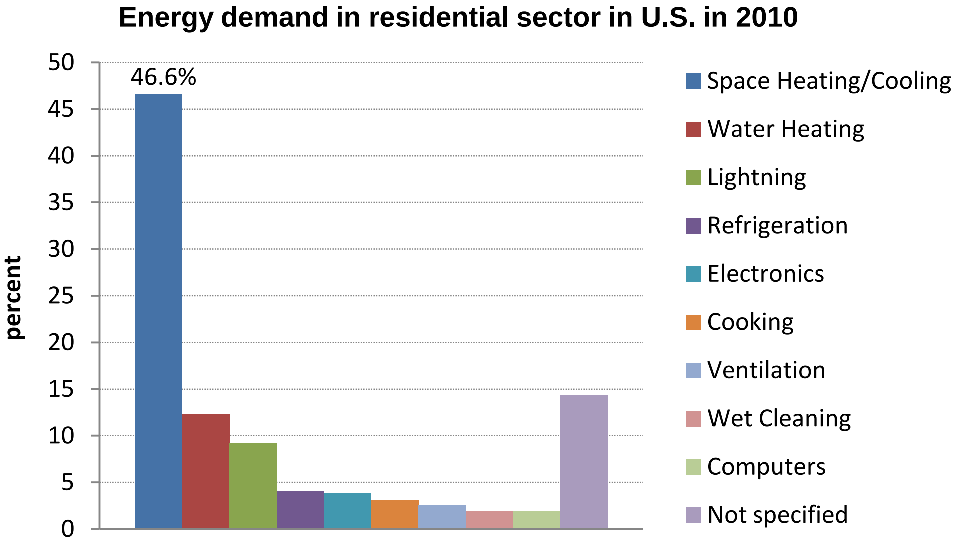


Figure 2.3.4: Energy Demand in the Residential Sector in the United States of America in 2010
Source: U.S. Department of Energy, Buildings Energy Data Book, 2012

Aiming at the reduction of environmental impact (according to Stern, decline of CO_2 concentration in the atmosphere to 350 ppm) caused by anthropogenic activities such as space heating and cooling, as well as water heating, which together represent the highest share of energy consumption in the residential building sector, may prove to be a powerful agent of change through an effective decrease in energy demand for buildings and thus has great potential in contributing to climate change abatement.

A right combination of different renewable energy technologies and the maximum utilization of renewable energy potential, results in an effective contribution to the abatement of climate change due to human activities. In the course of this thesis, the focus will be placed on the deployment of solar energy in buildings for space heating and cooling. To reduce the effects of energy demand in existing buildings is a target of this paper. It is, however, of utmost importance that energy demands of buildings decline, for example through the application of passive architecture such as wall as well as window insulation, to avoid heat loss. Once that is accomplished, then solar energy application is cost-effective. Moreover, dealing with heating and cooling in buildings, this thesis will handle solar thermal energy technologies for the heating and cooling processes due to the higher efficiency in energy collection compared to the energy capture of photovoltaic cells. “A thermal system typically captures about 60% of solar energy, where PV cells convert less than 20% of the solar energy to electricity” (Austin Solar AC, 2009).

3. Technical Background

3.1 Introduction to Solar Heating and Cooling

“Changes in the standards of thermal comfort in the urban microclimate and in the capital cost of air-conditioning equipment have drastically increased the energy consumption in the building sector over the last decade” (Papadopoulos et al., 2003).

Traditionally, when technological development was not yet advanced, depending on the climate of the region, passive building design measures were taken to either reject excess heat of the Sun to cool indoor temperatures or increase thermal heat gain to warm the desired area. With growth of innovation, knowledge and technology, heating and cooling equipments were introduced and spread, demanding energy, primarily delivered by the combustion of fossil fuels, which is easily available and the least expensive for the individual compared to other energy sources. Furthermore, with the effortless accessibility of energy from fossils, building design with respect to passive heat gain and prevention became less significant. However, with the escalating environmental impacts such as air pollution and climate change, in addition to the fear of resource scarcity, renewable energy solutions are becoming more attractive. Due to the current rise of public awareness, education, political will and continuous research and development in the field of renewable energy technology, energy production from natural resources is establishing new competition in the energy market.

People spend as much as 80-90% of their lives indoor (Fischl, 2006). Thus, the provision of a comfortable atmosphere in the interior of a building is of high essence. A great deal of comfort can be measured by air temperature, humidity as well as air stream velocity that prevail in rooms. In this case, heating or cooling may become an issue. The main reason for going for solar heating and cooling is the use of sustainable and clean energy source (sun), which means a potential decrease of energy demand from polluting sources such as fossil fuels or wood combustion. The main disadvantage of conventional air conditioners is their high electricity consumption to drive the cooling process, which results in the concern of high energy demand that is associated with the need for more combustion of dirty and unhealthy fossil fuels, if chosen as an energy source. 80% of the world's population rely on coal, oil and natural gas as their energy source (Sangster, 2010).

Maximum electricity peak loads occur during the highest energy demand. In extreme cases this may lead to blackouts due to overloaded grids. The main points of attractiveness regarding solar cooling are the parallel curves of energy availability (sun) and energy demand (cooling). Solar thermal collectors harness solar radiation (Figure 3.1.1), which undergoes a transformation directly into usable heat. This heat may then be utilized to heat space or water in a building. However, this heat source may also be used to drive a cooling device to condition a building. Moreover, the great advantage lies in the enhancement of the efficiency of air conditioners, powered by solar energy, with rising solar radiation input. In geographical regions which, due to climatic conditions, require cooling but also heating during the year, one and the same solar thermal technology may be utilized for both the cooling and heating of a building. Technically, cooling and heating are two sides of the same coin: for both purposes a temperature difference (a hot and a cold side) is needed.

Regarding environmental protection, solar heating and cooling offers a two-way approach: on the one hand it reduces energy demand in the building sector, thus CO_2 emissions, and on the other hand, completely eliminates the need for harmful refrigerants, such as CFC, HCFC or HFC.

Note that solar thermal application is a direct heat circle with a hot and a cold side. Yet, to complete the cooling and heating system of a building, some electricity is required to drive machines such as compressors, pumps, ventilators etc. With the combination of photovoltaic cells as a support electricity source, the system may become independent from the polluting energy source of fossil fuel combustion and thus be self-sufficient.

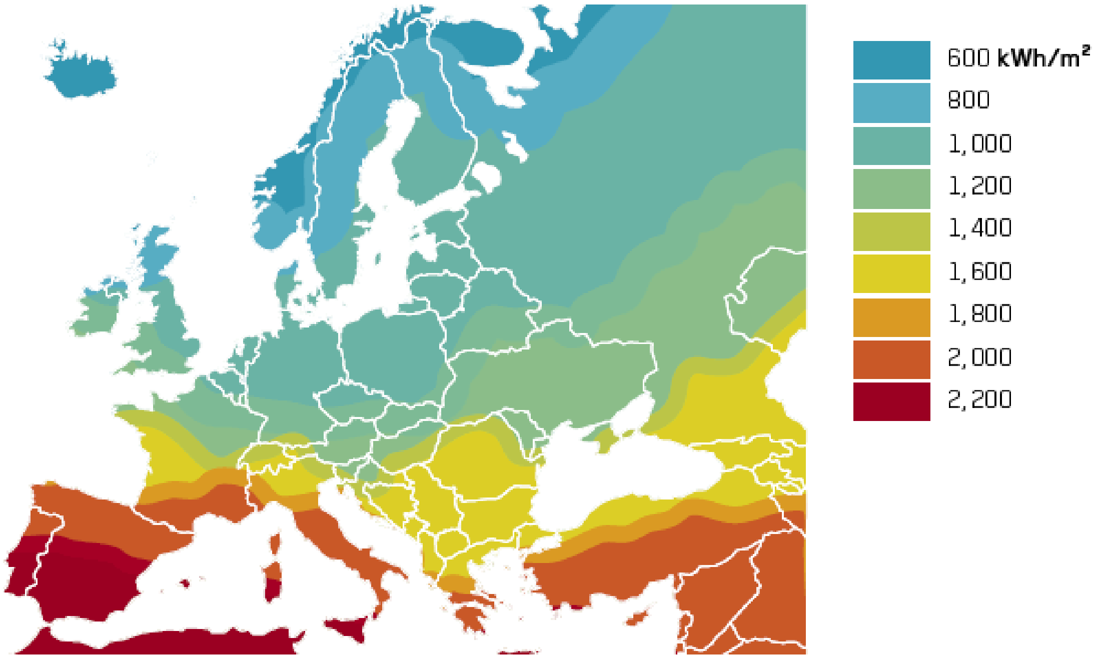


Figure 3.1.1: Solar Irradiation per Year, Europe
Source: Sapa Solar homepage

A solar thermal system, for heating and cooling purposes, involves the installations of various components (Figure 3.1.2). The direct link between the source (Sun) and the target (hot water utilization), is the solar thermal collector, a “special kind of heat exchanger” (Sözen et al., 2008), as it has the task of converting the sun’s radiation into heat. The conversion occurs by means of the physical radiation law of a blackbody, in this case, a dark-coated plate, called absorber, inside each tube of the solar collector, which absorbs solar radiation. In the tube an arrangement of pipes is filled with a heat transfer fluid, typically water, antifreeze water or air (Kalogirou, 2004), which takes up the produced heat. The produced heat is then stored in tanks for further application. A distribution system allocates the heat according to the need, whether as hot water or as heat source for the cooling device. The chiller produces cold water which is stored in a tank (optional), then further distributed to the air handling unit for air conditioning. To put this into perspective, Figure 3.1.3 demonstrates a solar thermal installation through a model house, which represents the example of implementation for heating purposes. The hot water produced by the solar thermal collector is distributed for the desired operation, for example, the hot water may flow through under-floor heating pipes to achieve indoor climate comfort by means of conduction, radiation and convection. The hot water may be distributed through the radiators placed in the rooms of a building. Another application is warm tap water for the kitchen or the bathroom. Further, the hot water can be utilized for wet cloth washing or for the dishwasher. In case solar heated water is fed into the washing machine, electric energy for heating up the water would be saved.

Figure 3.1.4 demonstrates a solar thermal installation for cooling purposes. The cold water produced, by thermally driven chillers, may be distributed to individual rooms of a building by a supply air duct. Another possibility of utilization is through under-floor cooling pipes. Figure 3.1.5 represents both cooling and heating installation combination possibility in a building.

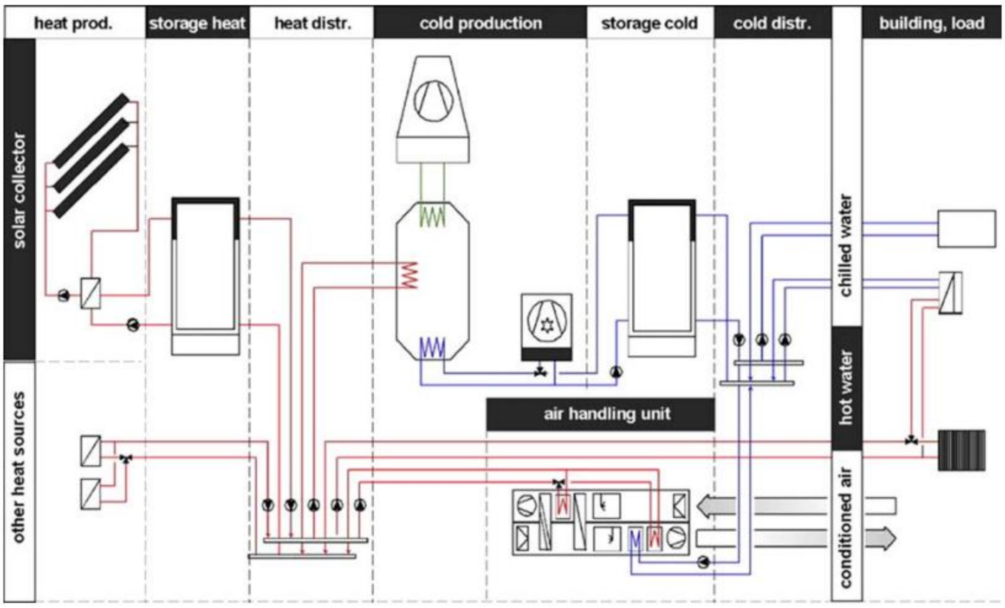


Figure 3.1.2: Schematic of Solar Air Conditioning System and Components
Source: Balaras et al., 2007

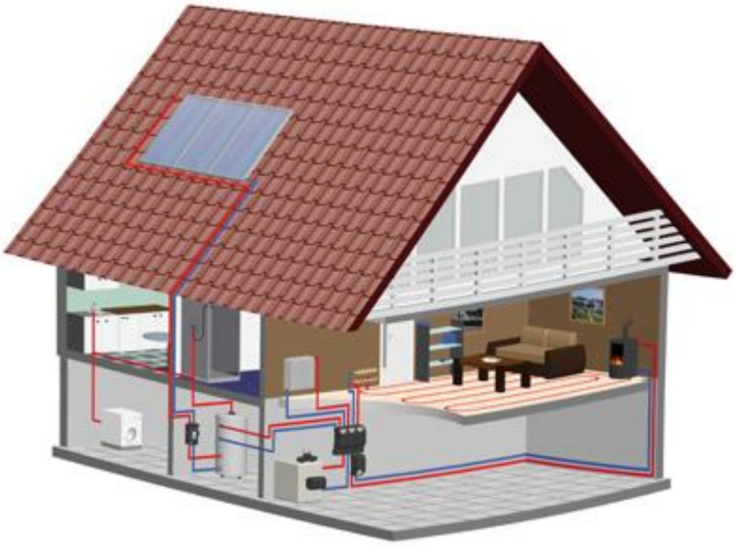


Figure 3.1.3: Solar Thermal Installation for Heating
Source: Renewable Energy World, 2011

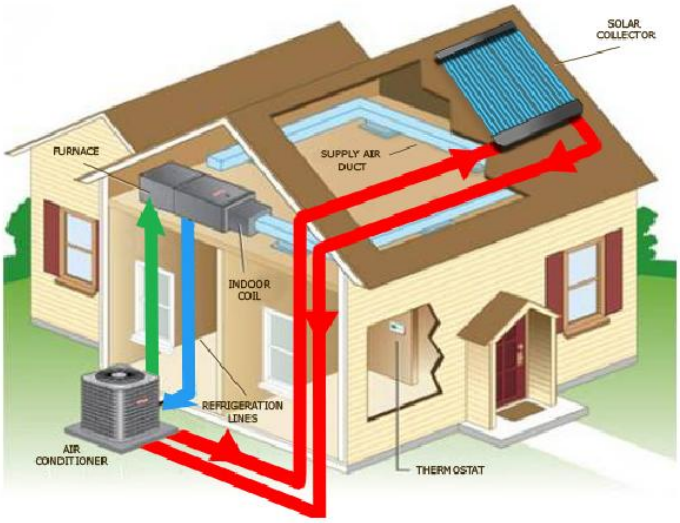


Figure 3.1.4: Solar Thermal Installation for Cooling
Source: Pepsolar homepage

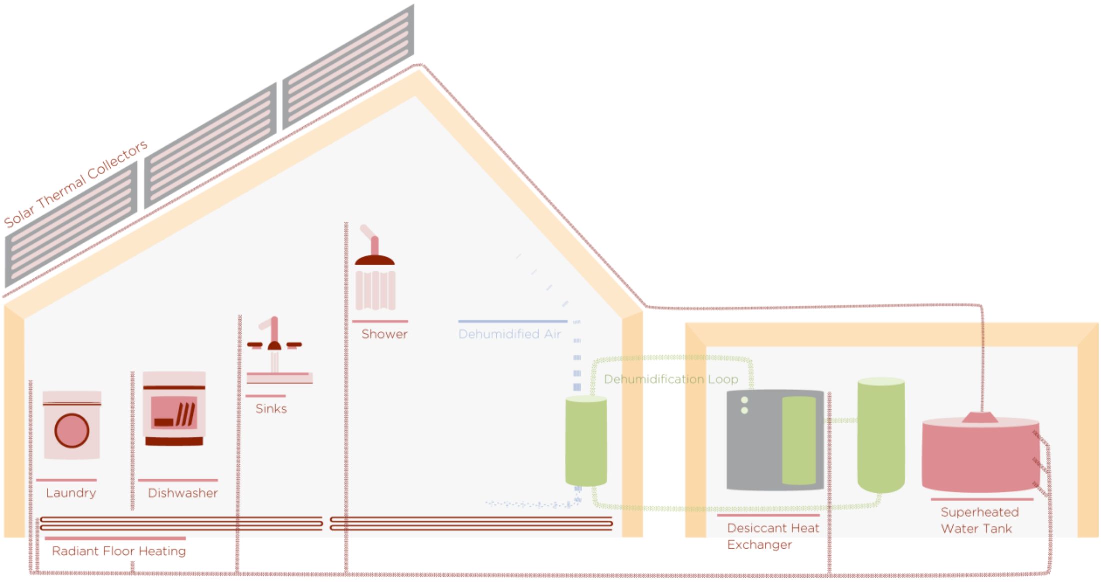


Figure 3.1.5: Solar Thermal Installation for Heating and Cooling
Source: University of Minnesota, Solar Decathlon, 2009

The technology systems suitable for solar air conditioning to achieve a conditioned room in a building without using harmful refrigerants are thermally driven chillers (absorption chillers and adsorption chillers) and desiccant cooling systems. In addition, the utilization of vapour compression chillers (electrically driven) to drive the cooling cycle has the advantage of providing a “cold back-up source in the solar air-conditioning system” (Alterner Project, 2002). These above-mentioned technologies are refrigeration machines which can be classified into open and closed cycle system.

Open cycle systems release the exhaust steam into the atmosphere, thus use only water as a refrigerant to eliminate the risk of causing environmental harm. This system applies desiccant cooling technology, providing cooled and dehumidified air.

In closed cycle systems the utilized refrigerant has no direct contact with ambient air, as it is condensed within the machine. Thermally driven chillers using absorption or adsorption technologies are prime components of the closed system. The chiller provides cooled water which is either supplied to the air handling unit or is distributed by a chilled water network to the individual rooms of the building for the operation of decentralized room installations such as fan coils or chilled ceilings.

Thermally driven chillers use a refrigerant (liquid or solid) such as chilled water or ammonia to extract the heat from the indoor air, producing a chilling effect to the required room. The system process involves phase state transformation of the refrigerant with the help of pressure difference, which in this case involves pumps, which are electrically driven. One of the characteristics of the refrigerant is that as pressure decreases so does its boiling point. This is an essential factor to allow a phase change of the refrigerant from liquid to gas without additional input of energy (heat).

A sorbent material, either Lithium-Bromide salt solution or water, having a higher boiling point than the refrigerant, is necessary in the system of thermally driven chillers, as they absorb the refrigerant (vapour in our case) due to its high affinity, converting it into liquid. During the procedure of absorption, heat is released, thus, to improve the absorption efficiency, the process should be cooled.

Desiccant cooling systems are thermally driven and use a refrigerant (liquid or solid) for cold production. However, unlike thermally driven chillers, they are open cycle systems, releasing the refrigerant steam exhaust into the atmosphere. The main advantage of desiccant cooling systems is that they are specifically useful in hot and humid regions because they condition as well as dehumidify the ambient air which is then ventilated (electrically driven) into the desired internal environment.

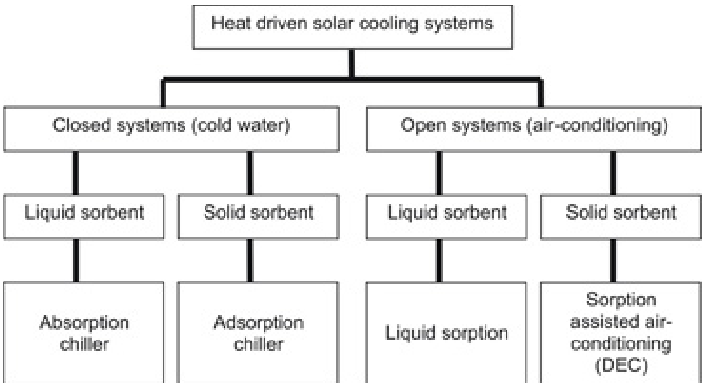


Figure 3.1.6: Classification of Solar Cooling Systems
Source: Jakob, 2008

To summarize, Figure 3.1.6 illustrates a clear overview of the solar cooling systems. Viewing the solar cooling system as a whole, the installations consist of several components including the solar collectors which harness the Sun’s energy, converting it into thermal energy (heat production). The captured heat energy is transported to the cooling device to drive the cooling process cycle (cooling production). Further installations such as pipes and pumps, control units like expansion devices and storage tanks are included within the necessary components (electrically driven). Detailed technical descriptions on solar thermal collectors and the various solar cooling systems which are under operation today are explained in the “Technical Excursion” Chapters of this paper.

3.2 Technical Excursion: Solar Collectors

3.2.1 Introduction to Solar Collectors

The primary task of the solar collector is to capture solar radiation, produce a conversion into heat and then transfer this heat to the downstream system (Sözen et al., 2008). Maximum energy capture can be achieved when the collectors are directed towards the equator, orienting southwards in the northern hemisphere and northwards in the southern hemisphere (Kalogirou, 2004). Furthermore, the optimum tilt angle should be “equal to the latitude of the location with angle variations of 10-15°, more or less depending on the application. The prevalent challenge of the solar thermal collector system is to transform sunlight “as completely as possible”, while relocating this heat “with low losses” (The German Solar Energy Society, Ecofys, 2005). Solar collectors are manufactured in various types (unglazed collectors, glazed flat-plate collector and vacuum collector) and designs, depending on the application, and are offered at different costs and performance efficiencies.

To enable a description of the collector’s geometry, the following definitions are used (Figure 3.2.1.1 and Figure 3.2.1.2):

- “The *gross surface area* (collector area) is the product of the outside dimensions, and defines for example the minimum amount of roof area that is requires for mounting,
- The *aperture area* corresponds to the light entry area of the collector - that is, the area through which solar radiation passes to the collector itself,

- The absorber (also called the effective collector area) corresponds to the area of the actual absorber panel" (The German Solar Energy Society, Ecofys, 2005).

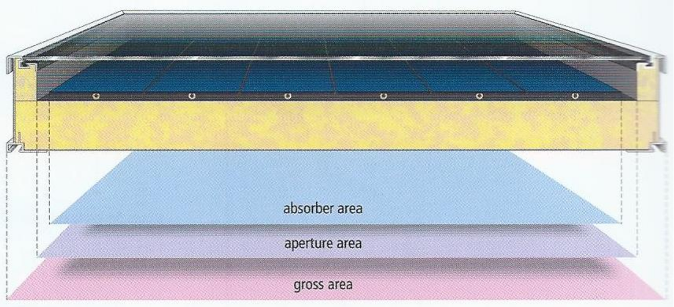


Figure 3.2.1.1: Definition of Geometry of Flat Plate Collectors
Source: Ecofys, 2005

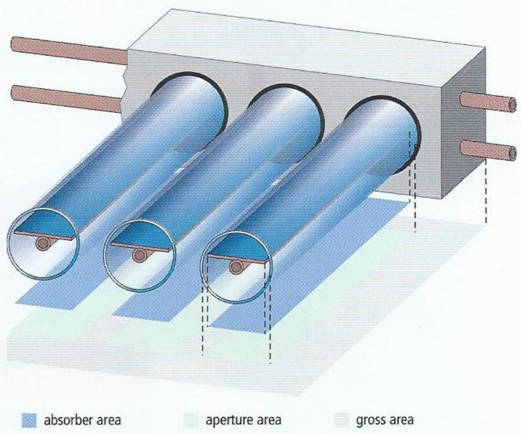


Figure 3.2.1.2: Definition of Surface Area of Evacuated Tube Collectors
Source: Ecofys, 2005

3.2.2 Unglazed Collectors

The simplest construction, and thus the most inexpensive construction of a solar collector, is the unglazed collector (Ecofys, 2005). As the name conveys, unglazed collectors have no glazing and furthermore have no thermal insulation as well as no housing (Figure 3.2.2.1 and Figure 3.2.2.2). They only consist of the absorbers (most important part of solar collectors). Lowest performance and highest thermal losses can be observed. Applications vary from swimming pool water heating to water preheating of residential buildings.

Figure 3.2.2.1: Unglazed Collector, Absorber
Source: Ecofys, 2005

Figure 3.2.2.2: Application of Unglazed Collector
Source: ledtechshop.com

3.2.3 Glazed Flat-Plate Collectors

Figure 3.2.3.1 shows the basic components of a flat-plate collector. The dark-coated (high absorptivity) absorber captures a large portion of energy, as solar radiation penetrates the transparent cover (glass or plastic (Sözen et al., 2008)). The heat transfer fluid in the absorber tube absorbs the heat, increasing its temperature to 30 to 70°C (Sözen et al., 2008), and is then transferred to the hot water storage tank or is directly used. To prevent heat losses, the collector box is well insulated to minimize conduction loss, while the transparent cover reduces convection loss and finally radiation loss is limited due to the ability of the glass to transmit the short-wave radiation of the sun but act as almost opaque to the emitted long-wave thermal radiation of the absorber plate (Kalogirou, 2004). Figure 3.2.3.2 illustrates the energy flow in the collector.

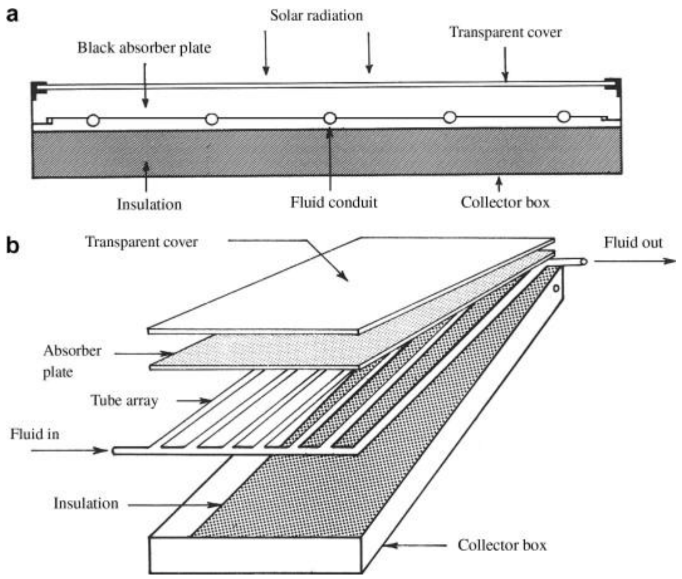
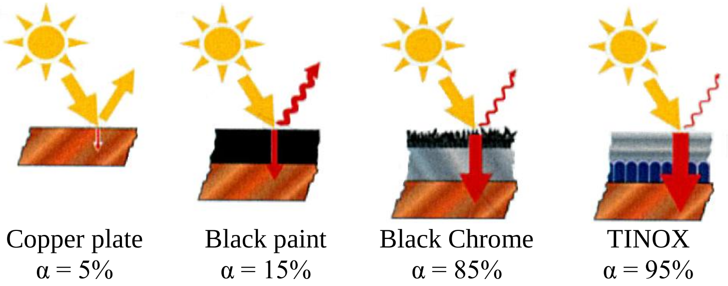


Figure 3.2.3.1: Schematic of Flat-Plate Collector
Source: Sözen, 2008

Figure 3.2.3.2: Energy Flow in the Flat-Plate Collector
Source: Ecofys, 2005

The absorber being the main part of the collector has the characteristic of high absorptivity and low emissivity, thus faces the challenge of absorbing as much solar radiation as possible to obtain maximum thermal yield while maintaining thermal radiation low. To alter absorption and emission behaviour, selective spectral coatings are used (Figure 3.2.3.3).



Copper plate
α = 5%

Black paint
α = 15%

Black Chrome
α = 85%

TINOX
α = 95%

Figure 3.2.3.3: Behaviour of spectral-selective coating of the Absorber
Source: Ecofys, 2005.

Most common applications of flat-plate collectors are for space heating and water heating (Sözen et al., 2008). They are usually mounted on the roof of the building (Figure 3.2.3.4)

Figure 3.2.3.4: Roof Integrated Flat-Plate Collectors – Residential Building in Denmark
Source: Renewable Heating & Cooling, European Technology Platform

3.2.4 Vacuum Collectors

The challenge of maintaining heat losses low, thus increasing performance, is effectively tackled by evacuated tube collectors. As the name reveals, the glass cylinders are evacuated and depending on the degree of vacuum, more heat loss may be suppressed. The evacuation minimises losses caused by convection and conduction of heat inside the collector system. With an evacuation to less than 10^{-2} bar, thermal losses through convection remain minimal, while a further evacuation prevents heat losses by means of conduction (Ecofys, 2005). As radiation requires no medium, it can only be maintained low by selective spectral coatings, as Figure 3.2.3.3 illustrates (Ecofys, 2005). Inside the glass tube, a dark absorber plate captures the solar radiation penetrating through the tube.

Applications of evacuated tube collectors include space heating and cooling as well as hot water production in the industrial, residential sector (Arora et al., 2011) as well as commercial sector – see Figure 3.2.4.3.

Figure 3.2.4.1 demonstrates the basic design and working of vacuum collectors. A number of tubes are joined and connected at their top part by “an insulated distributor or collector box” (Ecofys, 2005) through which the heat transfer fluid runs (Figure 3.2.4.2).

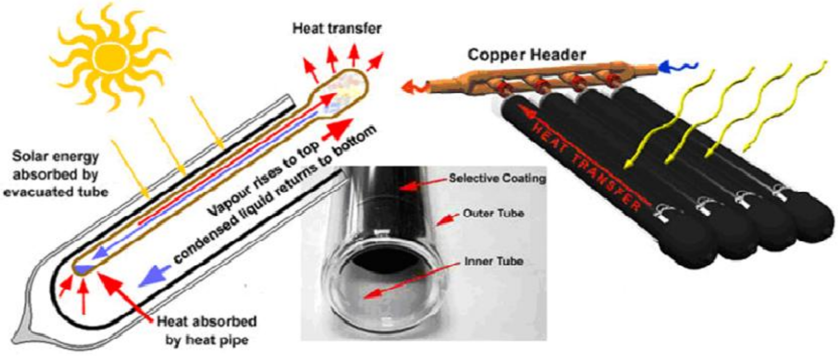


Figure 3.2.4.1: Basic Design and Working of Vacuum Collectors
Source: Arora et al., 2011

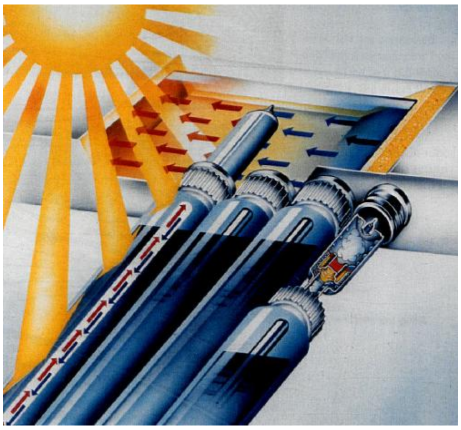


Figure 3.2.4.2: Heat Transfer Fluid Flow in an Evacuated Tube Collector
Source: Ecofys, 2005

Figure 3.2.4.3: Evacuated Tube Collectors Application (Hotel in Rome, Italy)
Source: Renewable Heating & Cooling, European Technology Platform

3.3 Technical Excursion: Cooling Devices

3.3.1 Sorption technology

The cooling process of solar air conditioning applies sorption technologies, referring to absorption, adsorption and desiccant cooling. Absorption and adsorption chillers are cooling machines, which generate cooling via a heat source (e.g. solar thermal energy). These chillers are known as ‘thermally driven chillers’, absorption chillers being most common in the commercial market compared to adsorption chillers (CIBSE CHP Group, 2012). In Europe, for example, 60% of all solar cooling systems apply the technology of absorption chillers, while 28% employ desiccant and the remaining 12% implement adsorption chillers (Sabatelli et al., 2005). These technologies are based on a refrigerant and a sorbent material, where the difference is found in the nature of the sorbent (liquid or solid) and the time length of the sorption cycle (Fan et al., 2007). The principle of the closed cycle system (absorption and adsorption) entails a refrigeration cycle involving four key components being an Evaporator and a Condenser as well as a Sorber and a Desorber. The latter pair replaces the electrically driven, mechanical compressor system of a conventional vapour compression system (Afonso, 2006). A more novel sorption technology relies on the principle of an open cycle dehumidification system with the utilization of a liquid desiccant technology. More common are solid desiccant, as just 6% apply liquid desiccant (Henning, 2007). The main advantage of desiccant cooling is that it provides thermal comfort in hot and humid climatic conditions.

3.3.1.1 Absorption Chiller

The Absorption cooling system utilizes heat, a refrigerant and an absorbent material to produce chilled water at around 6-12°C (GE Energy, 2012). Components of the Absorption Chiller include an Evaporator, an Absorber, a Desorber (also known as Generator and Extractor) and a Condenser (Figure 3.3.1.1.1). Each of these modules are heat exchangers, as the principle of absorption cooling is based on enthalpy for phase change, making the capture and release of heat an elemental procedure in this type of cooling system. The machine operates under pressure differences of high and low to enable a circulation of the refrigerant within the system (Bhatia, 2004). Low pressure is required at the evaporation stage of the refrigerant to allow its vaporization at a low saturation temperature. The main task here, at this stage, is to remove the heat from the room (which requires conditioning), thus, consequently producing the demanded cooling effect. Note that in case of air leakage, causing loss of vacuum, the machine efficiency is negatively affected. The high pressure is then required to compress the previously produced refrigerant vapour into refrigerant liquid. This process, in addition, separates the refrigerant from the absorbent. The main task, at this stage, is to reject the heat that was removed from the room which is subject to cooling. The pressure in the evaporation stage is about ten times lower than in the condensation stage (Bhatia, 2004).

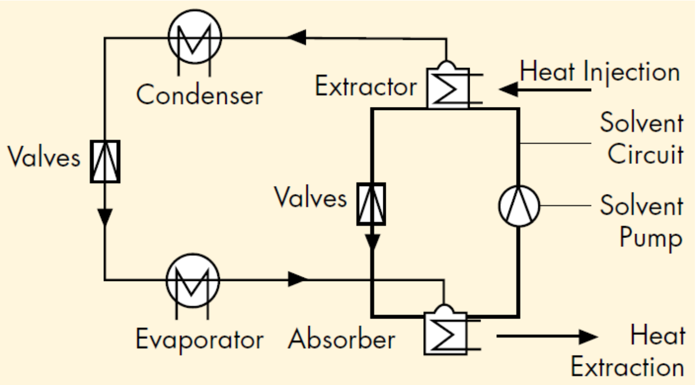


Figure 3.3.1.1.1: Schematic of Absorption Chiller
Source: BINE, 1998

The following text explains step by step the processes undertaken in an Absorption Chiller:

Step 1: In the **Evaporator,** the desired cooling of the circulating system water is produced via the phase change of the refrigerant from liquid to gas. As the liquid refrigerant in the evaporator coil with low pressure and low temperature enters the Evaporator, it extracts heat from the circulating chilled water contained in tubes. Due to the low pressure, the absorbed heat evaporates the refrigerant, thereby producing the desired chilling effect (cooling process). To avoid an increase of pressure in the vessel, which could be formed by the evaporation process, the refrigerant vapour is removed from the Evaporator into the lower pressure interior of the Absorber (next stage). Physically, the Evaporator and the Absorber are enclosed by the same casing.

Step 2: In the **Absorber**, the refrigerant vapour is condensed to liquid as it is absorbed by the absorbent (lithium-bromide, LiBr, salt solution), releasing the heat it had absorbed during the evaporation process in the Evaporator. A continuous migration of the refrigerant between the two vessels is achieved as a consequence of the pressure difference (high in the Evaporator due to evaporation and lower in the Absorber due to absorption) in addition to the affinity of the absorbent for the refrigerant. To increase the efficiency of the absorption process, the heat released is absorbed by the **cooling water**, which is circulated through the Absorber and connected to the Condenser.

Step 3: The diluted absorbent is pumped electrically (unless the system contains a bubble pump) into the **Generator** (Desorber/Extractor). In this vessel, the refrigerant undergoes another phase change from liquid to gaseous form. This evaporation process occurs due to the high temperature steam or water flowing through tubes acting as a heat source (e.g. from solar thermal collectors) that is delivered to the Generator vessel. The main task here is to heat, thus, evaporate the water from the diluted absorbent, to separate the refrigerant from the absorbent. The concentrated absorbent is brought back to the Absorber while the refrigerant vapour flows to the Condenser filling the surrounding space.

Stage 4: The **Condenser**, as the name conveys, condenses the incoming refrigerant vapour, converting it into liquid, under high pressure. The heat transfer is accomplished by the **cooling water** received from the Absorber and continuing its migration to a **cooling tower**. The condensed refrigerant liquid is collected at the bottom of the vessel exiting in high pressure and high temperature. Due to the closed cycle of the absorption cooling system, the refrigerant leaves the Condenser to flow back into the Evaporator, where the cycle starts again. However the high pressure refrigerant is first throttled via a **control unit** (expansion device), down to the Evaporator pressure. The main task of this expansion device is to maintain the pressure difference between the Condenser and Evaporator.

Absorption chillers can be classified under three types:

1. Single-effect: This cycle concerns the refrigerant and absorbent through the main components – Evaporator, Absorber, Generator and Condenser.

2. Double-effect: This refrigeration machine involves two Generators and two Condensers for a higher efficiency.
3. Triple-effect: This type is still under development and represents the next improved generation of absorption technology.

The single-effect chiller requires the least heat supply temperature for its operation, but offers the least efficiency. Higher driving temperatures can achieve higher efficiency performances by the evolution of double- and triple-effect chillers (Figure 3.3.1.1.2).

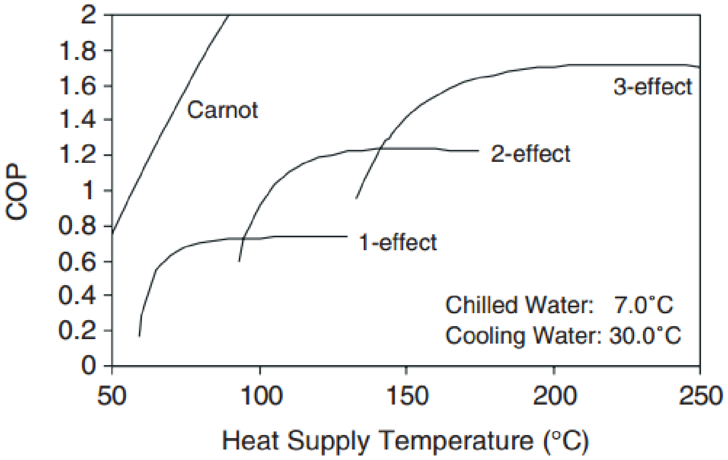


Figure 3.3.1.1.2: Coefficient of Performance and Heat Supply Temperature of 1-effect, 2-effect and 3-effect chillers
Source: Balaras, 2007

3.3.1.2 Adsorption Chiller

In the absorption chiller, as explained above, the refrigerant is absorbed by an absorbing solution, while in the adsorption chiller, the refrigerant is adsorbed (collected) on the internal surface of a dry and highly porous solid, thus the name Adsorption Chillers (Sabatelli et al., 2005). Current market available working pairs are water as refrigerant and silica gel or zeolite as adsorbent material. The adsorption chiller consists of two adsorbent compartments, called Receiver and Generator, which substitute their duty to switch between cooling and heating to maintain the adsorption and desorption process of the refrigerant running simultaneously, unlike absorption chillers, which consist of one continuous loop.

The Adsorption Chiller consists of a pressure vessel, divided into four chambers; Receiver, Generator, Evaporator and Condenser. A heat exchanger is installed in each chamber, allowing for phase changes of the refrigerant throughout the system process. Physically (Figure 3.3.1.2.1), the chambers are connected by flap valves with the Receiver and the Generator next to each other, the Evaporator at the top and the Condenser at the bottom.

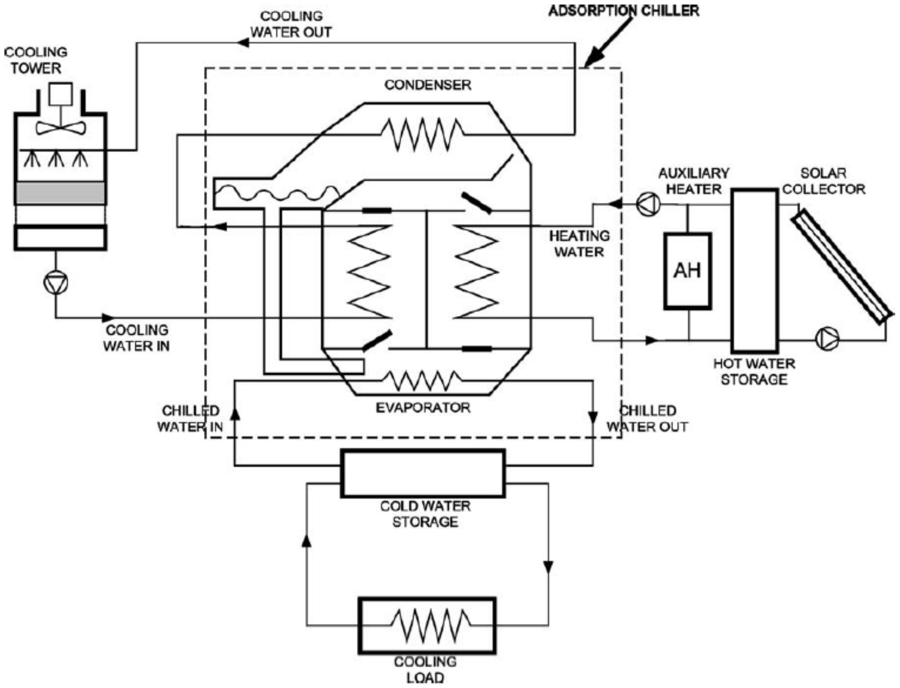


Figure: 3.3.1.2.1: Schematic of Adsorption Chiller
Source: Papadopoulos et al., 2003

The adsorption chiller operates under complete vacuum, thus, for the initial start of the adsorption chiller, a vacuum pump is activated (electrically driven) to evacuate the entire pressure vessel, and within five to seven minutes (GBU mbH, 1995) the machine operates fully automatically. The refrigerant is sprayed into the **Evaporator** and evaporates under low pressure, similar to the absorption chiller, thus obtaining the useful cooling effect. The valve connected to the **Receiver** is open to allow the refrigerant vapour to flow inside, getting adsorbed by the adsorbent as vapour. When the chamber is saturated, the valve connecting to the Evaporator closes while the valve to the Condenser opens. Heat is added via a thermal heat source, thus switching from Receiver to **Generator** mode. Through this heat, the refrigerant is desorbed and migrates as vapour to the **Condenser**, condensing due to a cooling cycle, changing its phase from vapour to liquid. The cycle completes and starts again (closed cycle) as the refrigerant liquid returns to the Evaporator.

Note, the Receiver and Generator is alternately heated and cooled. While the Generator, which includes the heating process, operates, the Receiver is simultaneously cooled via a cold water flow to allow heat transfer, extracting heat created by the adsorption process. All connecting valves operate by means of pressure differences in the chambers during operation.

3.3.1.3 Desiccant Cooling System

Desiccant cooling is an open cycle system, thus the refrigerant is discarded into the environment from the system after the desired cooling effect is provided while new refrigerant is supplied. Only water in this case is used as a refrigerant (ESTIF, 2006), since direct contact with the atmosphere is involved. Desiccant cooling utilizes the principle of ab/adsorption, where water vapour is ab/adsorbed from the ambient air to the sorbent due to the pressure difference of water vapour in the air and vapour pressure of the sorbent. The theory behind desiccant cooling systems is that ambient air is dehumidified first then cooled or heated to the desired temperature. Components of the system include a Desiccant Wheel, a Heat Recovery Wheel (or Thermal Wheel), an Evaporative Cooler (also known as Humidifiers) and/or a Cooling coil or another Evaporative Cooler and a Generator.

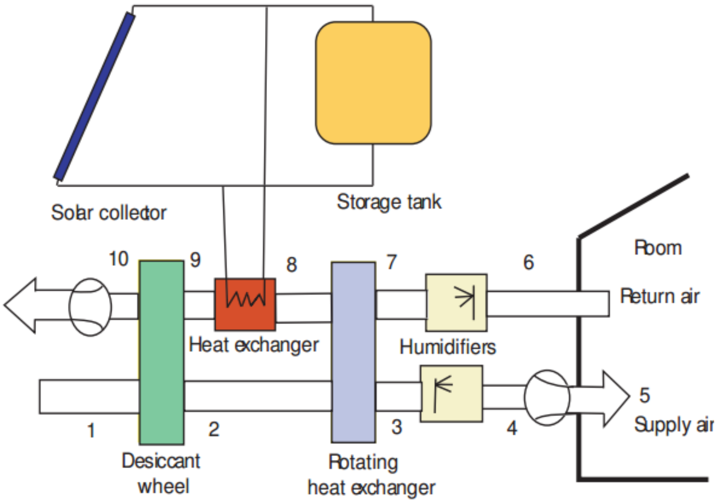


Figure 3.3.1.3.1: Schematic Drawing of a Desiccant Cooling System
Source: Wurtz et al., 2005

Following the schematic drawing of a desiccant cooling system (Figure 3.3.1.3.1), the **Desiccant Wheel** is a rotating wheel (electrically driven) equipped with a desiccant, which is a hygroscopic material such as silica-gel (solid) or lithium chloride (liquid) (ESTIF, 2006) as a sorption material. As hot and humid ambient air passes through the wheel, moisture is adsorbed (silica-gel) or absorbed (lithium chloride) by the desiccant, thus dehumidifying the air, consequently heating the air due to the heat release of the ad/absorption process. In case of the liquid desiccant, a higher dehumidification is achieved, in addition to the potentially high energy storage due to the possibility of the concentrated solution storage (ESTIF, 2006). The purpose of the **Heat Recovery Wheel**, which is a heat exchanger, is to pre-cool the air stream. If the supply air contains the desired moisture content then the **Cooling Coil** further cools the air flow to the wanted temperatures. However, if the moisture content still requires controlling, then the **Evaporative Cooler** (Humidifier) provides for the desired indoor air temperature and moisture content ventilated into the interior of a building. The exhaust air from the room enters the second Evaporative Cooler, to be cooled up to saturation. The air flow then passes the Heat Recovery Wheel again to uptake the energy which had been extracted earlier, before the air was supplied to the building. Temperature of the air stream must be further increased by the **Generator**, powered by solar thermal energy, to reach the regeneration level of the desiccant so to regenerate the Desiccant Wheel, where the desiccant is dried and moisture ejected.

Figure 3.3.1.3.2 illustrates the process of a desiccant cooling system under typical climatic conditions of central Europe. The ambient temperature shown in the illustration is 32°C, with a relative humidity of 40% (1), while the internal environment is 26°C with a relative humidity of 55% (5). Through the desiccant cooling process a supply air temperature of 16°C with a relative humidity of 93% is achieved (4).

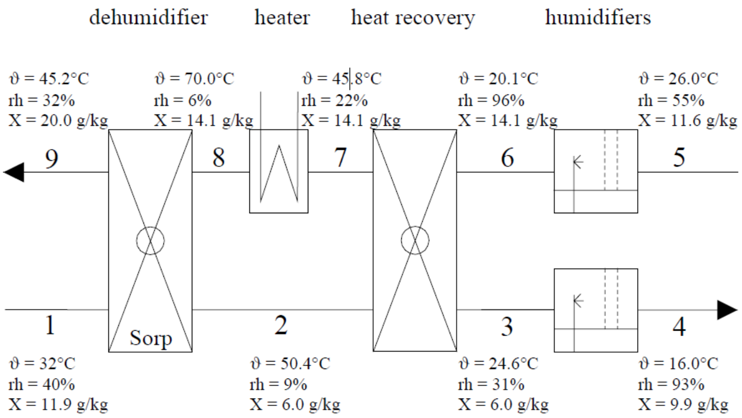


Figure 3.3.1.3.2: Process of Desiccant Cooling System under Typical Climatic Conditions of Central Europe
Source: Höfker et al., 2001

3.3.2 Evaporative Cooling

Evaporative cooling, as the name says, cools and humidifies the air stream by means of evaporation. However, two classifications of Evaporative Cooling require distinguishing, the direct and indirect system.

3.3.2.1 Direct Evaporative Cooling

Direct evaporative cooling directly supplies the evaporatively cooled air flow to the desired conditioned space (Figure 3.3.2.1.1). Applying latent heat evaporation, the cooling process occurs though the phase change of water from liquid to vapour while energy supply remains constant. The result is that warm ambient air becomes, through direct evaporative cooling, cool moist air.

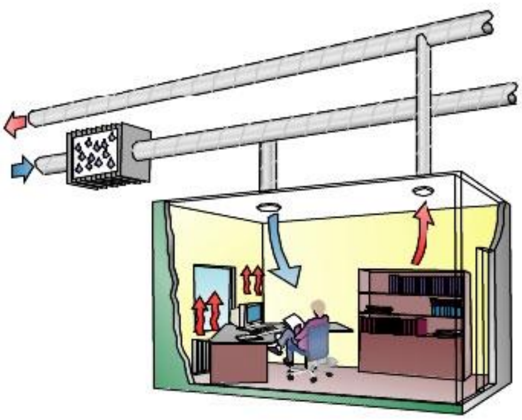


Figure 3.3.2.1.1: Principle of Direct Evaporative Cooling
Source: Akcor, 2008

Comparable to Desiccant Cooling, Evaporative Cooling is also an open cycle system, discarding the exhaust air into the environment. A closed cycle system takes indoor air and recycles it, while evaporative cooling draws ambient air into the room. Thus, for efficiency, an open window or door needs to be maintained at the farthest distance from the cooling machine, to allow the added air to escape. The main components of the system include a Fan, Evaporative Pad, Blower, Water Pump and Float Valve. The basic principle of the technical process (Figure 3.3.2.1.2) involves the drawing of warm ambient air by a large **Fan** through wet **Evaporative Pads** positioned in front of the fan, thus evaporating and cooling the air flow. The **Blower** ventilates the cooled air into the indoor environment of the building. The Water not evaporated trickles down due to gravity into a pool at the bed of the cooler device. This water is re-circulated by a Water Pump, repeating the process. Due to the continuous loss of water caused by evaporation, a **Float Valve** is responsible for the refilling when water level becomes low.

The ambient air which flows through the Evaporative Pads evaporates water from the surface of the material, preventing water droplets from being ventilated into the interior room of the building. In case of high air-flow speed, eliminators are required (Rona, 2004).

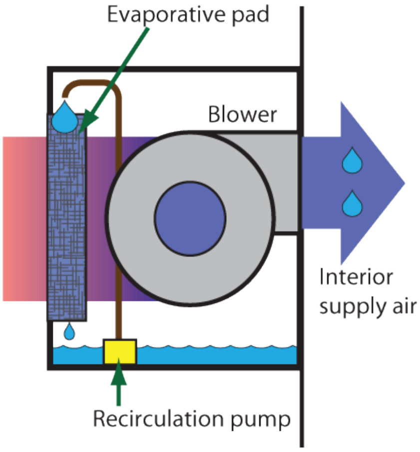


Figure 3.3.2.1.2: Direct Evaporative Cooling Device
Source: Energy Design Resources, 2010

3.3.2.2 Indirect Evaporative Cooling

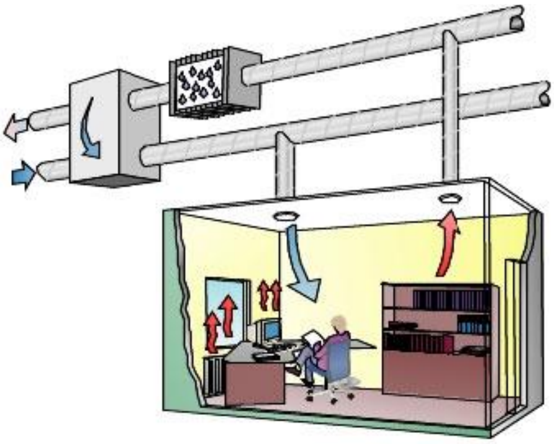


Figure 3.3.2.2.1: Principle of Indirect Evaporative Cooling
Source: Akcor, 2008

Unlike in the case of direct evaporative cooling, the cool humidified air stream does not come into direct contact with the conditioned space, thus does not increase room humidity level because no moisture is added to the conditioned space air stream (Figure 3.3.3.2.1). Recycling of indoor air is possible when utilizing this system (Palmer, 2002), which is noteworthy because the re-circulated air temperature would be lower than the ambient air temperature, thus requiring a reduced amount of cooling capacity to sustain comfortable indoor conditions. Indirect Evaporative Cooling can be brought into connection with Direct Evaporative Cooling, known as In/direct Evaporative Cooling, increasing efficiency (Palmer, 2002).

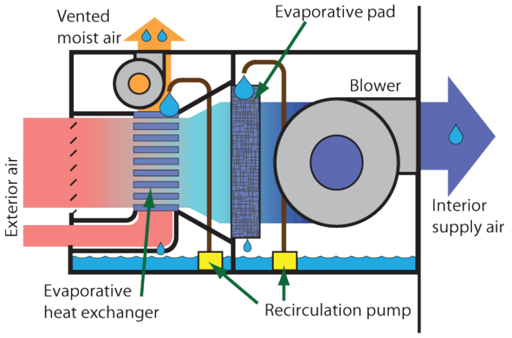


Figure 3.3.2.2.2: Indirect Evaporative Cooling Device
Source: Energy Design Resources, 2010

Components of the Indirect Evaporative Cooling include a Heat Exchanger, a Blower, an Evaporative Pad and a Recirculation Water Pump (Figure 3.3.2.2.2).

Warm indoor air from the building (secondary air stream) is extracted and evaporatively cooled by an **Evaporative Cooler**, following the same principle of Direct Evaporative Cooling. The secondary air stream then passes through one part of the **Heat Exchanger**, while the other part draws warm ambient air (primary air stream). The cool and moist evaporatively cooled secondary air stream cools the primary air stream by heat transfer within the heat exchanger. Finally the cooled dry primary air stream is ventilated into the conditioned space by a **Blower**.

3.3.3 Technical Overview of Cooling Devices

Table 3.3.3.1: Technical Overview of Absorption Chiller, Adsorption Chiller and Desiccant Cooling
Source: ESTIF, 2006

Method	**Closed cycle**		**Open cycle**	
Refrigerant cycle	Closed cycle system – Recycling of refrigerant with system		Refrigerant (water) is released into the atmosphere	
Principle	Chilled water		Dehumidification of air and evaporative cooling	
Phase of sorbent	solid	liquid	solid	liquid
Typical material pairs	water-silica gel	water-lithium bromide or ammonia-water	water-silica gel or water-lithium chloride	water-calcium chloride or water-lithium chloride
Market available technology	Adsorption chiller	Absorption chiller	Desiccant cooling	Close to market introduction
Typical cooling capacity (kW cold)	50 – 430 kW	15 kW – 5 MW	20 – 350 kW (per module)	
Typical COP	0.5 – 0.7	0.6 – 0.75 (single effect)	0.5 - > 1	> 1
Driving temperature	60 -90°C	80 – 110°C	45 – 95°C	45 – 70°C
Solar collectors	Vacuum tubes, flat plate collectors	Vacuum tubes	Flat plate collectors, solar air collectors	

Table 3.3.3.1 illustrates a comparison between absorption chiller, adsorption chiller and desiccant cooling, with the most essential technical details. Driving temperature is the required water temperature provided by the heat source, such as solar thermal collectors, to operate the cooling machine. COP is the Coefficient Of Performance, which represents a basic parameter of efficiency of thermally driven chillers. COP is

defined as “the fraction of heat rejected from the chilled water cycle (‘delivered cold’) and the required driving heat” (ESTIF, 2006).

$$\mathbf{COP_{thermal} = Q_{cold} / Q_{heat}}$$

The drawback of COP is that it does not include the electrical consumption required by the components of the solar thermal installation such as pumps, fans, ventilators etc. To precisely compare different technologies, therefore, account should be taken of the total energy input. Note that the smaller the value of COP, the less efficient is the chiller and the more energy input is required, i.e. higher driving temperature.

4. Verification of Hypothesis – A Case Study of Greece

4.1 Hypothesis

The hypothesis states that the replacement of traditional energy by solar energy (input) in the housing sector can contribute remarkably to carbon dioxide mitigation.

A common trait of residential buildings is that they consume three to five times more energy than public buildings (Theodoridou et al., 2011).

The experimental part of this thesis is a case study of Greece, a climate favourable for the deployment of solar energy. Data for the following case study have been collected from literature. However, some estimations, approximations and assumptions will be necessary so to produce final values and present a concrete conclusion. The objective of this case study is to contribute to the reduction of CO_2 emission in order to partly tackle the global challenge of climate change abatement by means of a technical approach of solar energy application instead of the conventional and polluting fossil fuel combustion.

4.2 Greek Renewable Energy Source Policies for CO_2 mitigation

In its current economic situation, Greece is facing a two-fold challenge of not only having to undergo economic development, but moreover, achieving this aim with limited greenhouse gas emissions. Encouraging investments in renewable energy sources (RES), Greece has established a constructive and positive legal framework. The Greek Ministry of Environment, Energy and Climate Change is the prime governmental body leading RES development. Greece, being an EU country, is legally bound, via the renewable energy directive 200928/EC, to achieve its target of 18% of RES regarding their final energy consumption. However, Greek's ambition is higher: national Law 3851/2010, entitled "Accelerating the development of Renewable Energy Sources to deal with climate change and other regulations addressing issues under the authority of the Ministry of Environment, Energy and Climate Change" states as follows: "Contribution of the energy produced from RES to the gross final energy consumption by a share of 20%". Furthermore, with regard to this thesis's subject of solar cooling and heating, this national law further aims at a "contribution of the energy produced by RES to the final energy consumption for heating and cooling to a share of at least 20%". Article 5 of Law 3851/2010 offers a price rationalization if energy is to be produced by RES, namely €264.85/MWh if "solar energy [is] exploited by solarthermal power stations" and a sum of €284.85/MWh is proposed if "solar energy [is] exploited by solarthermal power stations with a system of storage, which secures at least 2 hours of operation at the nominal load". Additionally, Article 10 (3) (3) states that it is "obligatory that part of the hot water use needs are covered by solar panels" if a building plan is "submitted to the relevant Planning authority after the 1.1.2011". Noteworthy is Article 10 (3) (4) which declares the obligation that as of 31.12.2019, "all new buildings will have to cover the total of their primary energy consumption with energy supply systems based on [among others] renewable energy sources".

All in all, Greek RES capacity will increase from 4500MW of 2010 to 19300MW by 2030 (Bellona Environmental CCS Team, 2010). This is a 400% increase.

4.3 Primary Energy

Greece's indigenous energy resources are substantially limited to coal, primarily lignite, which has the most significant share of 81% to the total primary energy production in 2009 (Eurostat, 2011). To date, 30% of the total lignite reserves have been extracted in Greece (EURACOAL). In 2010, lignite production accounted for 56.5 million tonnes, from which 27.4 TWh out of the country's total power generation of 47.9 TWh, which is 75%, were produced from Greek lignite fuelled thermal power stations (EURACOAL). Worth mentioning is the phase-out of a "vast majority of currently operating but outdated lignite units" by 2024 (Bellona Environmental CCS Team, 2010).

When reviewing Greece's gross inland energy demand, it is oil that dominates as an energy source, not native lignite. The country is dependent to 99.7% on oil imports, according to 2009 data (EIA, 2010). The total energy demand in 2009 (Figure 4.3.1) accounted to 30.629 ktoe, out of which 55% was oil. Lignite, natural gas and renewable energy account for a share of 27%, 10% and 6%, respectively (Eurostat, 2011). The leftover of 2% is for hard coal and other minor sources. The annual average growth rate of total primary energy supply has been 3% from 1973 to 2008 (EIA, 2010).

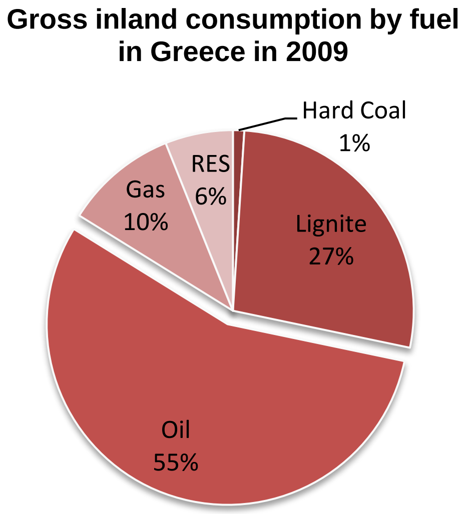


Figure 4.3.1: Gross Inland Consumption by Fuel, Greece, 2009
Source: Eurostat, 2009

One reason for Greece’s favouring of oil, which requires import, instead of native lignite, may be the low quality of Greek lignite coal, thus requiring treatment before combustion, whereas some of the oil comes ready for use and is therefore user friendly, an important aspect for e.g. the household sector. Six out of the ten oil terminals in Greece receive crude oil to be refined within the country (EIA, 2010). Greek’s lignite constitutes low calorific value between 3.770 and 9.630kJ/kg, a high water content ranging from 41 to 57.9% and a high ash content of 15.1 to 19%, each depending on the site of exploitation (EURACOAL). The sulphur content is low and lies between 0.4 and 1% (EURACOAL). Furthermore, it is essential to mention that in 2010 about 37.5% of the current lignite-fired power plants have reached an operational life of 30 years (Gnansounou et al., 2005), thus renovations or substitutions of aged units are necessary.

To satisfy the country’s energy demand, Greece imports oil, solid fuels, natural gas and electricity. Table 4.3.1 shows the development trend of net energy import of the different energy sources until 2009, further comparing Greece to Portugal due to comparable size of population and weather conditions as well as GDP. As a contrast, data from Germany, a highly industrialized country, is compared and finally, for the sake of completion, figures of the European Union (EU-27) are given.

Table 4.3.1: Net Imports of Solid Fuels, Oil, Natural Gas and Electricity, Greece, 2009
Source: Eurostat, 2011

Solid fuels (thousand tonnes)	**1999**	**2004**	**2009**
Greece	1.108	725	296
Portugal	6.001	5.257	4.995
Germany	126.050	43.024	40.248
EU	135.279	197.596	178.353

Oil (thousand tonnes)	**1999**	**2004**	**2009**
Greece	17.839	21.825	18.963
Portugal	16.720	15.597	12.758
Germany	126.050	119.269	108.311
EU	513.087	573.853	553.827

Natural gas (Petajoule)	**1999**	**2005**	**2009**
Greece	57	108	138
Portugal	91	181	198
Germany	2.666	3.058	3.130
EU	8.521	11.972	12.454

Electricity (GWh)	**1999**	**2005**	**2009**
Greece	164	3.780	4.367
Portugal	- 860	6.824	4.776
Germany	1.040	- 4.566	- 12.273
EU	11.660	11.310	15.134

4.4 Renewable Energy Sources

The production of energy in Greece from Renewable Energy Sources (RES) in 2008 is presented in Figure 4.4.1. Renewable energy power stations, excluding hydro power stations, enhanced their power generation from 163 to 2.811 GWh between 1999 and 2009 (Eurostat, 2011). Weighted against other renewable energy sources, hydropower shows the highest share of power generation, experiencing an increase from 4.592 to 5.258 GWh, between 1999 and 2009 (Eurostat, 2011). Compared to thermal power stations, however, Greek capacity of power generation ascended from 44.640 to 52.909 GWh (Eurostat, 2011). In total, Greece reveals its increase of power generation from 49.395 to 60.978 GWh, to satisfy the increasing demand of power for the Greek population (Eurostat, 2011).

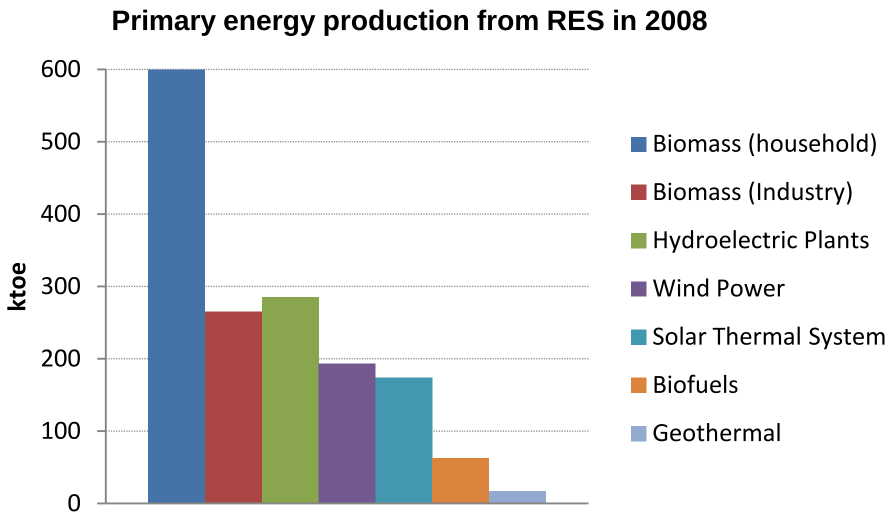


Figure 4.4.1: Primary Energy Production from Renewable Energy Sources, Greece, 2008
Source: Koroneos et al., 2011

The share of renewable energy in gross final energy demand exhibited an increase from a total of 7.2% in 2006 to 8% in 2008 (Eurostat, 2011). Greece has a binding target of 18% of RES to be reached in 2020 (Eurostat, 2011), another 10% as of 2008 values. Comparing Greece to Portugal, the latter country achieved a RES share rise from 20.5% in 2006 to 23.2% in 2008 (Eurostat, 2011). Portugal’s 2020 target is a total share of 31% of RES (Eurostat, 2011). Germany, however, is fairly comparable to Greece, with a slight advantage of almost 1%. Having an 8.9% share of RES in final energy demand in 2008, also Germany aims for 18% in 2020 (Eurostat, 2011).

Figure 4.4.2 shows Greece’s forecast power generation from the varying technologies and fuels from 2010 to 2020. A clear and steady drop of lignite and petroleum as sources for energy production can be identified, while on the other hand a large increase in power will be provided by natural gas and wind. Photovoltaic installations as well as geothermal and biomass/biogas will have a smaller share in power generation, whereas for hydropower no significant increase of future potential can be seen.

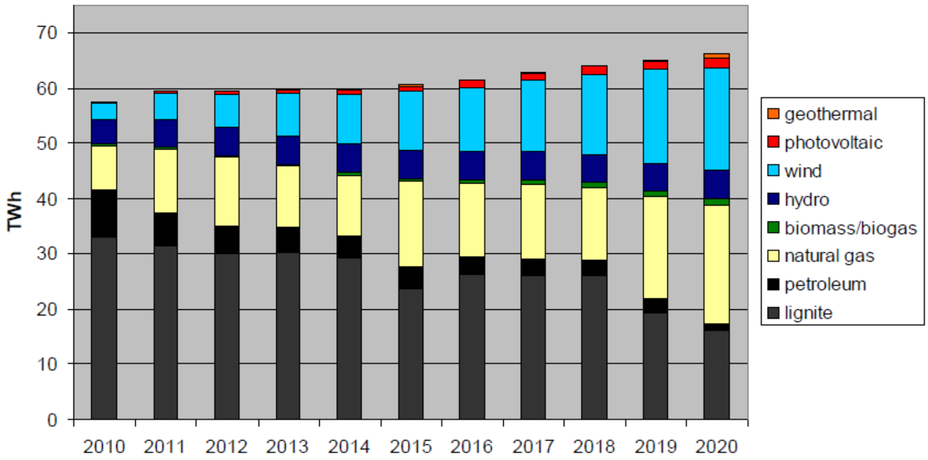
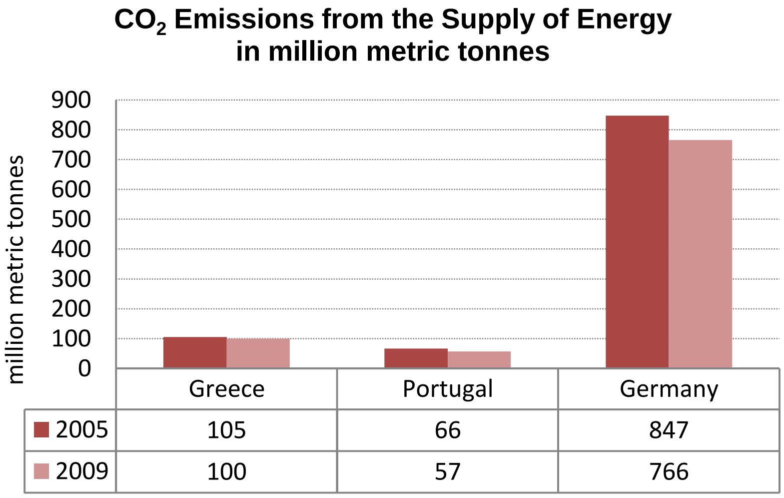


Figure 4.4.2: Estimated Power Generation from the Different Technologies/Fuels until 2020
Source: Centre for Renewable Energy Source and Saving (CRES), 2010

4.5 CO_2 Emissions from the Demand of Energy

The essence of the analysis (see the Chapter on *Primary Energy*) of the energy sector is mainly to understand the reasons and sources of carbon dioxide emissions. However, this is now clear and straightforward, as 94% of the total energy supply is based on greenhouse gas emitting fuels. Viewing the countries used as examples, Greece, Portugal and Germany, all three countries have reduced their CO_2 emissions between 2005 and 2009, as Figure 4.5.1 illustrates



	Greece	Portugal	Germany
🟥 2005	105	66	847
🟥 2009	100	57	766

Figure 4.5.1: CO_2 Emission from the Supply of Energy, a Country Comparison
Source: U.S. Energy Information Administration (EIA)

With regard to Greece, it is essential to go into details regarding energy demand, as this is the key player in CO_2 emissions, and then investigate the individual energy sectors to search for potential niches where clean and renewable energy may be replaced as alternative sources to mitigate emissions.

In 2008, 82% of total greenhouse gases were emitted from the energy sector (Koroneos et at., 2011). Figures 4.5.2, 4.5.3 and Table 4.5.1 illustrate final energy demand in Greece. In ten years, 2000 to 2010, energy demand has slightly increased from 18.56 to 19.03 Mtoe, which may, at first glance, not seem significant. Nevertheless, detailed analysis of the change of energy demand over these years is crucial in order to understand development trends. Generally seen, these four energy sectors have experienced a constant rise of energy utilization, but have at some point after the second half of the decade decreased their consumption. This is the reason for the outcome of the small increase within ten years. The most energy demanding sector in Greece is transportation, road transport being the most impact (Eurostat, 2006). Within the European Union, it is also this sector with the most rapid growth of energy demand and thus production of greenhouse gases. Next in line, regarding energy consumption, is the household sector, with an overall increase between 2000 and 2010 from 44.86 to 46.32 Mtoe. The peak was reached in 2005 with an energy utilization of 54.97 Mtoe, with a constant decrease ever since. The industry sector ranks third, with a consumption of 44.47 Mtoe in 2000, peaking in 2007 with 46.01 Mtoe then steadily declining, reaching 34.71 Mtoe in 2010. The service sector demands the least energy, showing a utilization of 13.10 Mtoe in 2000, but showing a constant growth until 2008, reaching its maximum of 22.16 Mtoe, since then decreased to 19.46 Mtoe in 2010.

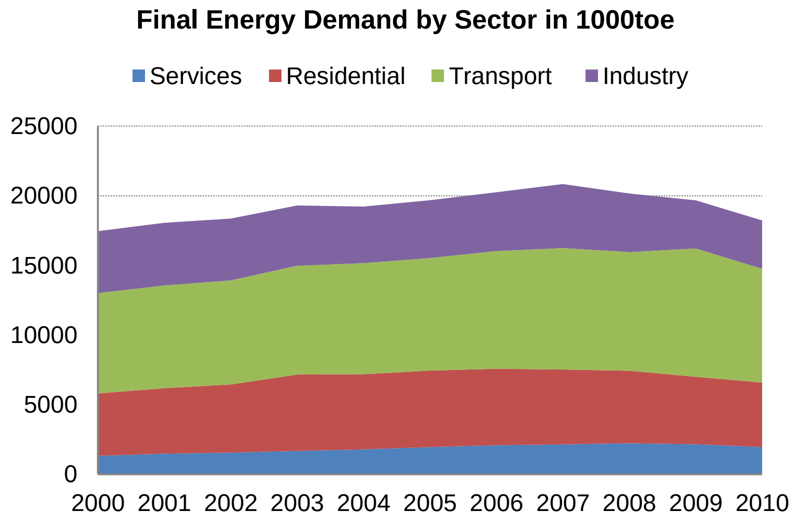


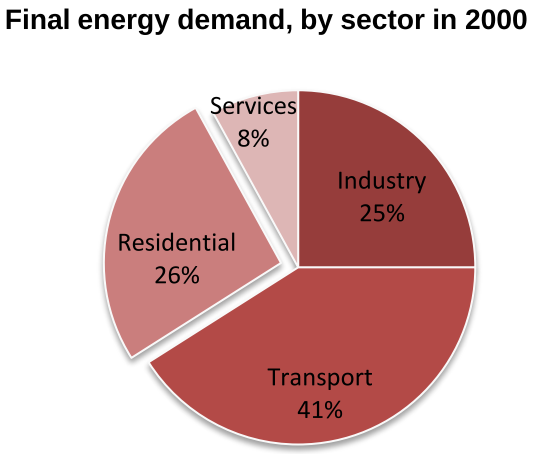
Figure 4.5.2: Final Energy Demand by Sector, Greece, 1000toe
Source: Eurostat

Table 4.5.1: Final Energy Demand by Sector, Greece, 1000toe
Source: Eurostat

	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010
Industry	4447	4504	4442	4327	4068	4158	4231	4601	4209	3462	3471
Transport	7212	7380	7478	7819	7978	8087	8458	8728	8525	9218	8177
Residential	4486	4702	4898	5488	5399	5497	5490	5377	5212	4848	4632
Services	1310	1470	1541	1666	1778	1939	2075	2134	2216	2143	1946

Regarding the use of alternative clean energy with the aim of the mitigation of CO_2 emission, renewable energy sources demonstrate a high implementation potential in the household sector.

In 2010, the European Commission published a study, revealing the CO_2 emissions by sector between 1990 to 2007 for all European Union Member States, as well as candidate countries and other European countries. Energy sectors were split into four main categories, namely Energy Industries, Manufacturing and Construction, Transport and finally Other Sources, each further divided into subcategories. Regarding Greece in the year 2007, Energy Industries, having the highest share, emitted 55.8%, out of which the subcategory Public Electricity and Heat Production dominates CO_2 emission with a 92.6% contribution. Manufacturing and Construction emit 10%, while Transportation shows a significant share of 22.2% of total emissions. Finally, Other Sources emit the rest, accounting for 12%, however, its subcategory Residential prevails with a share of 67.9%. It is thus to conclude and restate that the household sector proves to have a great potential regarding the implementation of renewable energy sources for climate change mitigation.



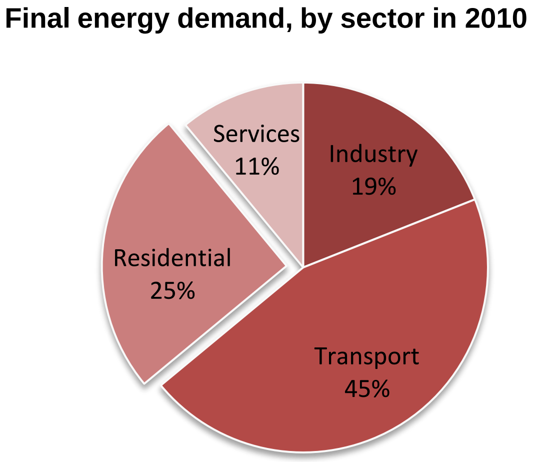


Figure 4.5.3: Final energy Demand by Sector, Greece, 2000 and 2010
Source: Eurostat

The key contributor of CO_2 emissions in Greece is the production of heat and electricity. This, however, is the global trend as well. The Intergovernmental Panel on Climate Change estimated global CO_2 emission to be 27 Gt, where electricity production alone emits 10 Gt, which is about 37% of the total emission (Koroneos et al., 2011).

The main energy sources for household space heating in Greece are oil products which in 2009 had a final energy demand of 56% (Eurostat, 2009). Remarkably notable is the increased share of renewable energy sources (solar) for domestic water heating from 22.3% in 1990 to 31.4% in 2004 (Giakoumi and Latridis, 2004). This development accounted for an electricity share decline from 40% in 1990 to 33.8% in 2004. The share of oil products for water heating, however, has ascended from 17.4% to 28.8% between 1990 and 2004. Greece utilizes energy during the summer months for cooling purposes. However, there is a deficiency of statistical data regarding this sector (Giakoumi and Latridis, 2004), as there are no official figures on energy demand. “The most common practice for cooling in Greece is to use air-conditioning units (e.g. split type). This, together with the increased need for cooling during summer months, increases the peak electric load, causing major problems in the country’s electric supply” (Giakoumi and Latridis, 2004). Out of this citation, we can thus legitimately assume 100% electricity consumption for air conditioning in Greece. According to the World Bank report 2011, sources of electricity are as follows: coal is the principle source of fuel, contributing the highest share of 45.1%, next in line are natural gas, oil and the hydroelectric sources, representing 27.2%, 12.6% and 10.9% respectively. Note that 84.9% of total electricity consumption for cooling is based on greenhouse gas emitting fuels. Furthermore, all taxes included, electricity prices for households in the second half of 2010 in descending order are Germany, Portugal then Greece with 32.4, 21.5 and 15.8 Euros per 100 kWh respectively (EIA, 2011). We can conclude that surely Geek electricity is subsidised, and Greece’s population may thus not have an incentive to invest in renewable energy source. However, Greece may generally over the long term save government expenses by strictly going renewable instead of electricity spending.

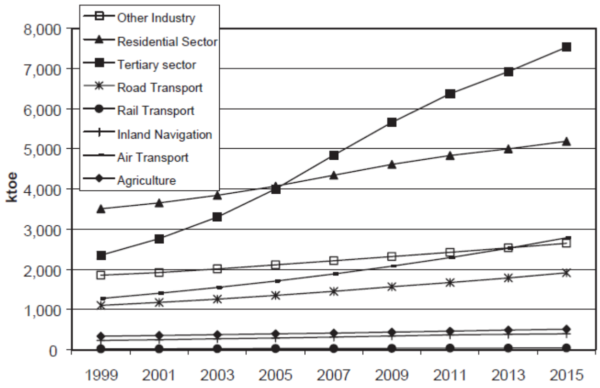


Figure 4.5.4: Energy Demand Forecast per Sector, Greece
Source: Agoris et al., 2004

Following Greece's energy trends for the past decade, forecasting efforts (R-MARKAL model) have been made regarding energy demand in various sectors (Figure 4.5.4). It can be clearly seen that the forerunners are the residential sector, which is overtaken by the tertiary sector in 2005, while the rest remain fairly constant over the years. According to the graph above, no decrease in energy demand is predicted.

4.6 Climate of Greece

Heating and cooling appliances in buildings consume a significant amount of energy, depending largely on the "climatic conditions, the architectural and constructive features of the building, the occupancy and the operational patterns, the various systems of heating and air-conditioning, the appliances and the other electromechanical equipments" (Papakostas et al., 2005).

The climate of Greece favours the application of solar energy, as it is a Mediterranean climate with long, dry and warm summers and "many hours of sunshine almost all year", while winter is short, mild and rainy (EEA, 2010). The summer months of July and August represent the hottest period of the year, but the warm season may last up to six months (April – September) a year. Average summer temperatures are approximately 25°C (SOLAIR consortium, 2008), while average maximum temperatures may reach 35°C (EEA, 2010). The coldest period of the year is between January and February. Average winter temperatures decrease depending on the exact location in Greece: maximum temperatures are felt near the coastal area, ca. 5-10°C, in mainland areas temperatures vary from 0-5°C, while in the northern region of Greece, temperatures may reach below freezing point (EEA, 2010).

Since the 1990s, an increase in temperature has been occurring in Greece, in particular in summertime, resulting in the rise of demand for air conditioning and high peak electricity (Tsoutsos et al., 2009). Further, a number of extreme weather conditions were experienced, including storms, heat-waves, floods but also drought (EEA, 2010).

4.7 Energy Demand for Heating and Cooling

In Greece, the average energy demand in the residential sector for cooling purposes amounts to around 35 kWh/m² per year, whereas heating demands up to 130 kWh/m² per year (SOLAIR consortium, 2008). This corresponds to a four-fold energy demand for heating purposes. Annual solar irradiation in Greece, seen on a daily basis, is averaged to be 4.6 kWh per m² (University of Oxford).

Today in Greece, space cooling by means of air conditioning "is exclusively based in the use of electric energy" (Koroneos et al., 2009). Whereas, the most common "heating system in Greek buildings is a central oil-fired boiler, distributing the heat produced to hydronic radiators" (Papadopoulos et al., 2008). From an environmental point of view, both these cooling and heating approaches contribute to vast amounts of CO_2, PM_{10} and SO_2. The recent introduction of natural gas in 1997 into the energy market (Koroneos et al., 2011), surely does serve as a fuel substitute to oil, but also releases these pollutants into the atmosphere. Thus, a great prospect for the utilization of solar heating and cooling is present.

In summertime, Greece's electricity demand rises due to cooling needs, as utilization of cooling, ventilation and air conditioning systems increases dramatically (Koroneos et al., 2009). This demand for comfort boosts the peak load of electricity, leading to an electricity supply dilemma (Giakoumi and Latridis, 2009). According to the CIA World Factbook, electricity consumption in Greece shows a constant increase over the years (2000 to 2011), as seen in Figure 4.7.1.

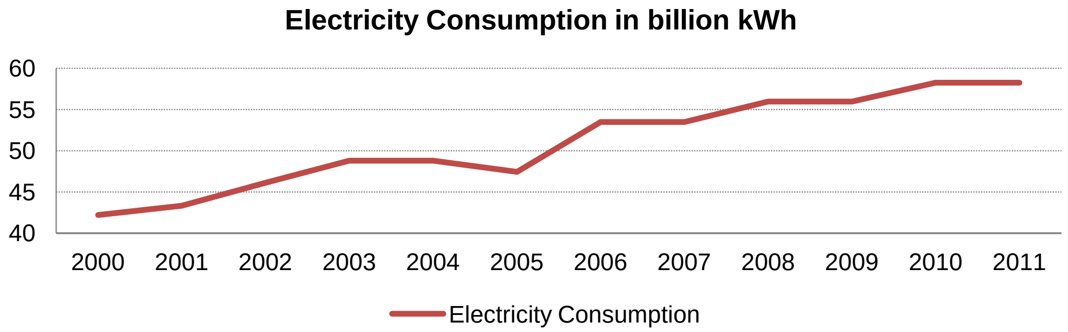


Figure 4.7.1: Total Electricity Consumption, Greece. 2000 to 2011
Source: Central Intelligence Agency (CIA) – The World Factbook

“Millions of air-conditioning units are in use around the world, the growth markets being the US and Asia in particular” (Thorpe 2011). Alone 2909 GWh/y (2.9 billion kWh/y) of total energy demand and a per capita utilization of 371 kWh/y, in 2003, in Greece, was dedicated for central air conditioning systems (Koroneos et al., 2009). In Greek public buildings, energy demand per square meter is 50 kWh/m² reaching up to 250 kWh/m² (Koroneos et al., 2009). Thus, a need for environmentally sound technologies is of high essence. In Greece, a packed air conditioning unit, which evidently is associated with high energy demand and greenhouse gas emissions, is most common in residential buildings as well as in many tertiary buildings (Argiriou and Mirasgedis, 2003). Furthermore, the demand for packed air conditioning units has risen by 200% within four years, between 1996 and 2000, as Figure 4.7.2 illustrates. In general, “global demand for Heating, Ventilation and Air Conditioning (HVAC) equipment is projected to rise over 6 per cent through 2014 to a market size of more than $88 billion” (Thorpe, 2011).

Figure 4.7.3 strongly illustrates the close relationship between electricity demand and annual seasons in Athens, Greece. Clearly, electricity utilization rises as temperature increases during summer. However, a much greater demand occurs during wintertime, peaking in December, which supports the energy demand analysis by SOLAIR, stated above, that Greece demands four times the energy for heating than for cooling. It is to be born in mind, on the other hand, that winter in Greece is “rather mild, and this is reflected both in the duration of the heating period and the mean and absolute minima of air temperature” (Papadopoulos et al., 2008).

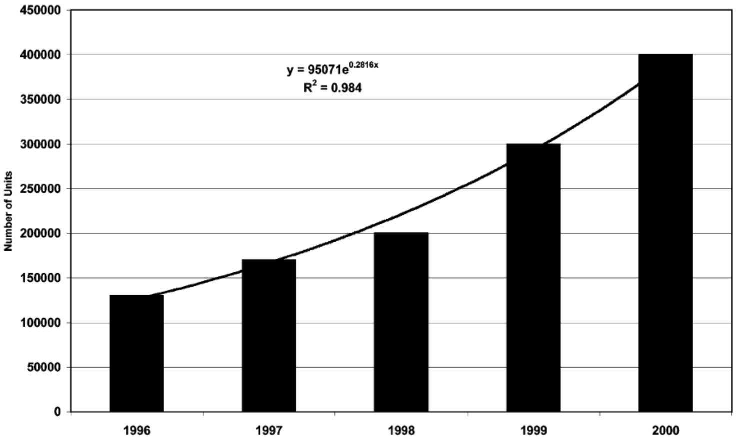


Figure 4.7.2: Sales of Packaged Air Conditioning Units Trendline, Greece
Source: Argiriou and Mirasgedis, 2003

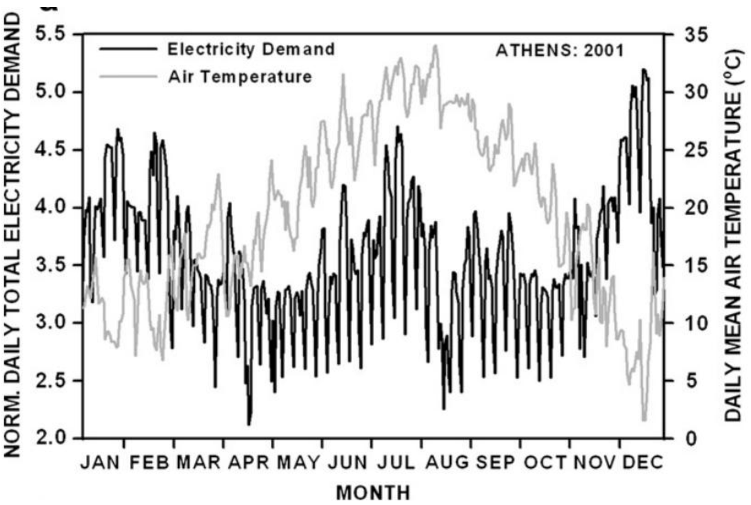


Figure 4.7.3: Variation of Normalized Daily Total Electricity Demand and Mean Daily Air Temperature, for Athens, Greece, 2001
Source: Psiloglou et al., 2009

Distinguishing between electricity demand and general energy, while further differentiating between heating and cooling loads (Figure 4.7.4) and its respective energy demands (Figure 4.7.5), it can be clearly seen that heating loads in winter require a higher power (up to 180kW) than the maximum cooling load in summer (up to 130kW). However, the maximum energy demand for cooling can be double in summer (20.000kWh) as in winter (11.000kWh).

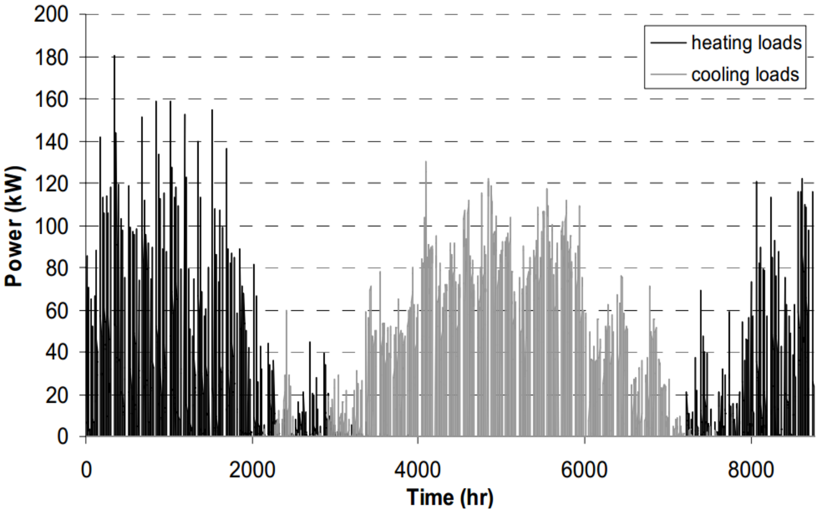


Figure 4.7.4: Heating and Cooling Loads over the Year, in Hourly Basis, Greece
Source: Tsoutsos, 2009

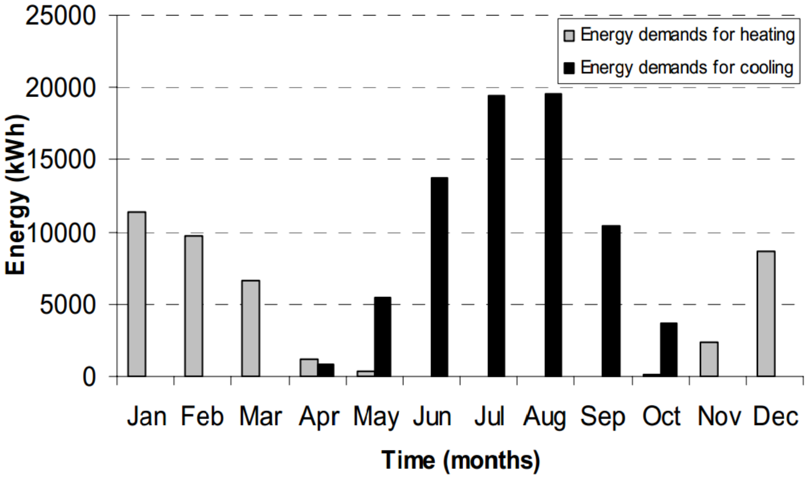


Figure 4.7.5: Heating and Cooling Loads over the Year, in Monthly Basis, Greece
Source: Tsoutsos, 2009

There is a large potential for the incorporation of renewable energy sources in the field of heating and cooling. Expected contributions until 2020 can be seen from Figure 4.7.6 forecasted by the Greek Centre for Renewable Energy Sources and Saving (CRES) and the "Fraunhofer Institut für Solare Energiesysteme" (ISE), where the gross final supply for heating and cooling by RES is presented.

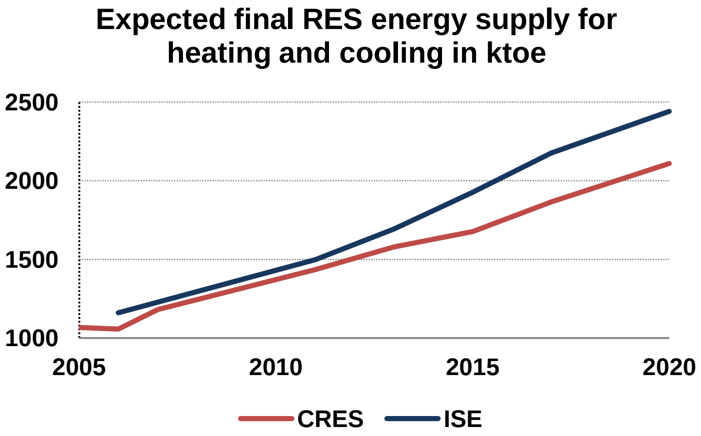


Figure 4.7.6: Expected Gross Final Supply for Heating and Cooling from Renewable Energy Sources, Greece, ktoe
Source: Caralis et al., 2010

Furthermore, Figure 4.7.7 illustrates the various renewable energy sources contributing to heating and cooling until 2020.

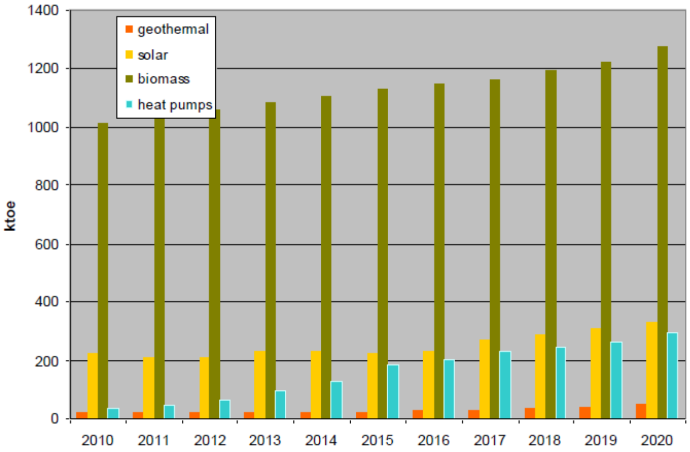


Figure 4.7.7: Estimated Contribution of the Different RES Technologies for Heating and Cooling, Greece, 2010 to 2020
Source: Centre for Renewable Energy Source and Saving (CRES), 2010

It can be clearly seen from Figure 4.7.7, that biomass shows a significant contribution from an early stage, and will steadily increase until 2020. Further, solar installations will also increase in Greece with a much less, but continuously increasing, share. A large increase of heat pumps will be installed, where the final energy contribution in 2020 will be comparable to that of solar energy. Geothermal plants will increase, but with an insignificant share, compared to the rest.

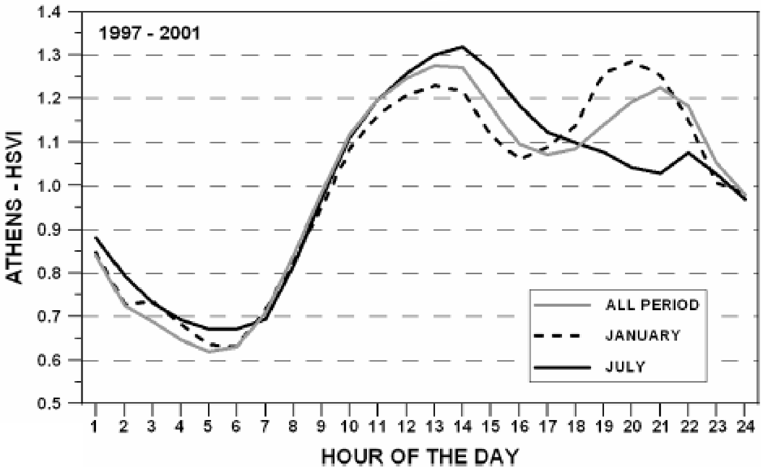


Figure 4.7.8: Hourly Seasonal Variation Index (HSVI) of Electricity Consumption, Athens, Greece, 1997-2001
Source: Psiloglou B. E. et al, 2007

The consumption of electricity in Greece's buildings is, among others, associated with heating and cooling (due to air conditioning) utilization patterns. Viewing electricity demand over a 24-hour period (Figure 4.7.8), consumption rises rapidly as the day begins, at roughly 6 a.m., remaining high the rest of the day, but peaking at noon and then again in the late evening. These consumption patterns are essential to note when dealing with solar heating and cooling, since solar radiation is the most important factor regarding the use of such technologies. Both heating and cooling processes with the use of solar energy require the availability of sunlight, therefore the installation of a thermal storage system as a back-up, during the lack of sunshine, is highly advisable. Solar heating and cooling technologies are an attractive option especially for the ideal climatic conditions such as in Greece. Surrounded by the Mediterranean sea, Greece “enjoy[s] high values of bright sunshine hours”, with mean sunshine duration values varying from the minimum of 75 hours per month during winter up to a maximum of 424 hours a month in summer (Matzarakis and Katasoulis, 2006). The Figure 4.7.9, illustrates the distribution of sunshine duration over the Greek region in winter and summer.

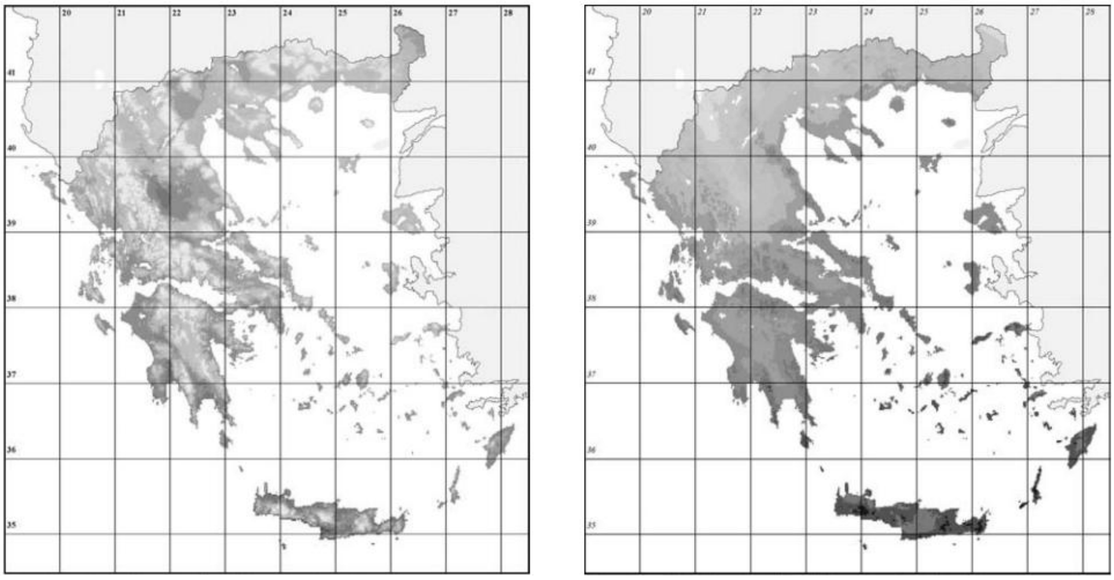


Figure 4.7.9: Geographical Distribution of Sunshine Duration during Winter (left) and Summer (right) in Hours, Greece
Source: Matzarakis and Katsoulis, 2006

4.8 Towards a final result – CO_2 mitigation efforts

For the purpose of contributing to CO_2 mitigation efforts in Greece, as well as for the sake of the case study of this thesis, data has been collected from literature. However, some estimations, approximations and assumptions will be of necessity so to produce final values and present a concrete conclusion. The objective of this case study is to contribute to the reduction of CO_2 emission in order to partly tackle the global challenge of climate change abatement by means of a technical approach of solar energy application instead of the conventional and polluting fossil fuel combustion. Further, the field of interest is the building sector in Greece, with the utilization of solar heating and cooling technologies. Throughout this thesis, solely solar thermal energy is referred to (photovoltaic technology could be used to drive electric devices for cooling, since demand and supply coincide). To put this into perspective, solar radiation is harnessed to produce hot fluid, not electricity. This provides the necessary source of heat to drive the heating and cooling process.

In the course of this paper, it has been found that the main resource for heating is oil, whereas cooling is primarily done by air conditioning and thus electricity is used. For this reason, the case study will assume that for the purpose of heating and cooling of all Greek buildings only oil and electricity, respectively, are consumed.

According to the Greece Building Census, Table 4.8.1 shows essential facts and figures which are vital when referring to solar heating and cooling.

Table 4.8.1: Key Figures Regarding Building Stock, Greece
Source: Pomonis, 2011

Population (2009 est.)	11.200.000
Buildings (2009 est.)	4.315.000
Dwelling Units (2009 est.)	6.630.000
Occupancy	77% Residential 23% Non-Residential 10.5% Mixed-Use

Remarkable is the high ratio of residential compared to non-residential buildings, as 77% out of all buildings in Greece are of residential use. From the figures given above, the number of residential buildings is 3.322.550. However, it is said that there are 6.630.000 dwelling units. Further, 26% of households in Greece suffer from fuel poverty, which means that more than 10% of income would need to be spent for energy (Santamouris et al., 2006). This will be incorporated in the calculations for this case study to enable more accuracy. Therefore, regarding the number of residential housing units in Greece, it will be assumed that 4.906.200 units can afford basic energy needs for heating and cooling.

Greece's building insulation code was introduced in 1979, imposing minimum thermal insulation standards for all buildings, not distinguishing between the three climate zones of the country. Regarding exterior walls, average U-values (air flow) have to be equal to or less than 0.7W/m²K and for roofs it must be equal to or less than 0.5W/m²K (Giakoumi and Latridis, 2009). However, buildings until 1990, have "deficient or even no thermal insulation at all" (Giakoumi and Latridis, 2009). This results in the current ratio of 71% of existing buildings in Greece with no insulation (Theodoridou et al., 2011). These facts are of high value as they explain one of the main reasons for the currently high energy consumption for buildings in Greece and similar nations.

In this case study, emphasis will exclusively be placed on the residential sector, as it "contributes significantly to the energy budget of the country and has such energy needs that match well the possibilities offered by solar thermal systems" (Argiriou and Mirasgedis, 2003). Moreover, a typical characteristic of residential buildings is their three to five times higher energy consumption compared to public buildings (Theodoridou et al., 2011). For these reasons, this case study will primarily focus on Greek households and their potential emission reduction if solar heating and cooling technologies were to be implemented.

4.8.1 Heating Case

The residential sector consumes around 15% of the total oil consumption in the country, as shown in Figure 4.8.1.1 (IEA, 2010). According to the CIA Worldfact book 2012, Greece's total oil demand in 2010 accounted for 371.300 bbl/d, thus, 55.695 bbl/d (one barrel equals 159 litres) was consumed by the residential sector. In 2007, space heating in Greece consumed 69% of total energy (Centre for Renewable Energy Source and Saving (CRES), 2009). Thus, calculated oil demand for space heating in the residential sector is 38.429 bbl/d. For the sake of this case study, this is the figure which will be used as a baseline of energy consumption for heating purposes in the residential sector. According to BP, one barrel of crude oil per day equals 49.8 tons of crude oil per year. Given that the Greek residential sector consumes for space heating purposes 38.429 barrels per day, which thus adds up to a total yearly crude oil consumption of 1.913.764 tons.

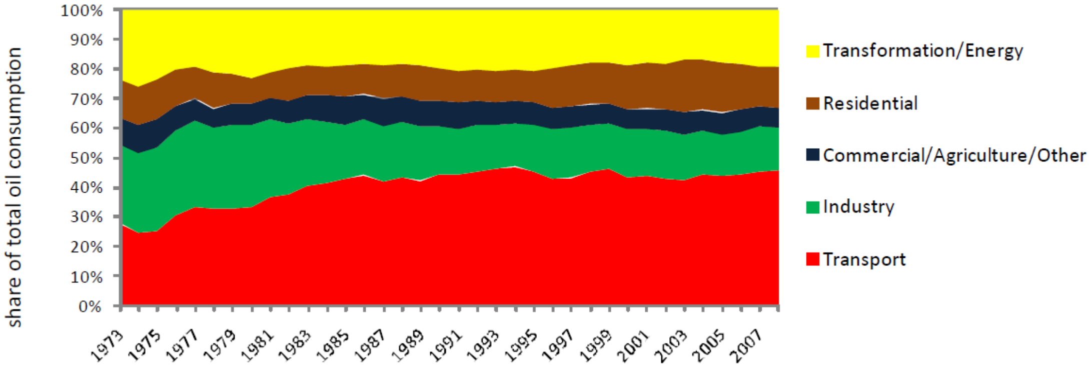


Figure 4.8.1.1: Oil Consumption by Sector, Greece
Source: International Energy Agency, 2010

According to the U.S. Environmental Protection Agency, a complete combustion (i.e. 100% oxidisation) of one barrel of crude oil consumption emits 433 kg of CO_2. Thus, in Greece's case, domestic space heating would be responsible for a carbon dioxide emission of 16.639.757 $kgCO_2$ per day. Given that 4.906.200 dwelling units can afford basic energy needs of heating and cooling, the CO_2 emission per dwelling unit accounts for approximately 3.4 $kgCO_2$ per day for space heating purposes alone. To obtain a more realistic amount of CO_2 emission per year from Greece, the number of days when heating is required will be discussed in the subsequent text.

According to Figure 4.7.5, Greece heats for eight months a year, peaking in January and February. However, Greece can be divided into three climatic zones (north, centre and south), which may represent different heating and cooling behaviours throughout the year, due to temperature differences among regions. One city from each zone will be chosen as an example for this case study to represent the whole county: Thessaloniki from the north, Athens from central Greece and Crete representing the southern part. See Figure 4.8.1.2 to gain a sense of orientation regarding the location of these named cities in the country.

For the sake of comparison, the heating behaviour of central Greece, (i.e. Athens), is given, which will act as the baseline: "the mean daily duration of heating [in Athens] is close to 7.5 hours per day [and] the average set point temperature for the heating period was close to 18.4°C" (Santamouris et al., 2006). Thus, for this case study, the temperature of 18°C will be selected as the trigger for the decision to heat a dwelling. Figure 4.8.1.3 gives the mean annual temperatures (maximum and minimum) of the three representative cities from the north, centre and south of Greece. Based on the temperature of 18°C and the maximum average temperature curve, people in the northern part of Greece require heating for six months a year, while the inhabitants of central and southern Greece heat for five and four months, respectively. Following the fact that in Athens people heat around 7.5 hours per day, these amounts of hours will be representative, in the course of the case study, for both the northern and southern part of the country.

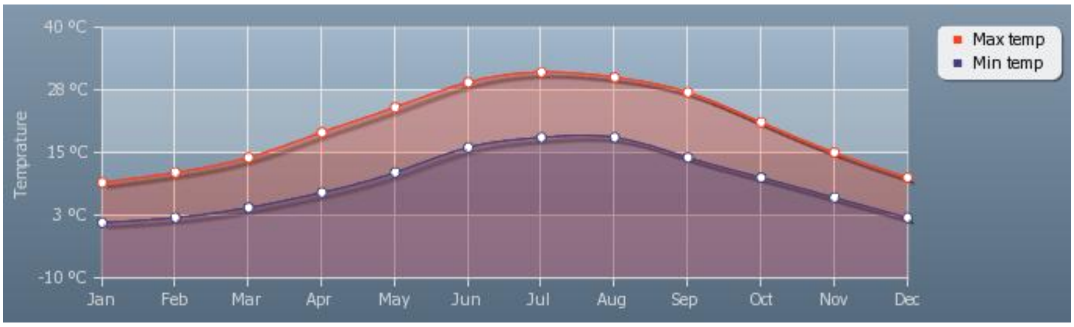
Concluding, one residential dwelling unit in northern Greece yearly consumes energy to heat residential buildings for 212 days, which indicates an annual CO_2 emission of 721kgCO_2/household/annum, bearing in mind that each dwelling unit emits 3.4kgCO_2 per day. Central Greece is responsible for 513kgCO_2 per household every year with 151 heating days, while heating in southern Greece illustrates the least environmental pressure with 411kgCO_2/household/annum, comprising of 121 heating days. However, the whole of Greece, with its 4.906.200 dwelling units, each emitting 3.4kgCO_2 per day, gives a total CO_2 release of 16.681.080kgCO_2 per day, solely for heating purposes, with average heating days of 161 days per year. This amounts to an annual carbon dioxide discharge of approximately 2.685.653.880kgCO_2/a, which is 2.685.654tCO_2/a into the atmosphere.

Concluding, if solar thermal technologies were to be implemented on 30% of Greek dwellings, a saving potential of CO_2 emission would amount to 805.696tCO_2 on a yearly basis. Table 4.8.1.1 gives figures on annual oil consumption, annual CO_2 emission as well as potential CO_2 saving if solar heating is applied for the residential sector in Greece.

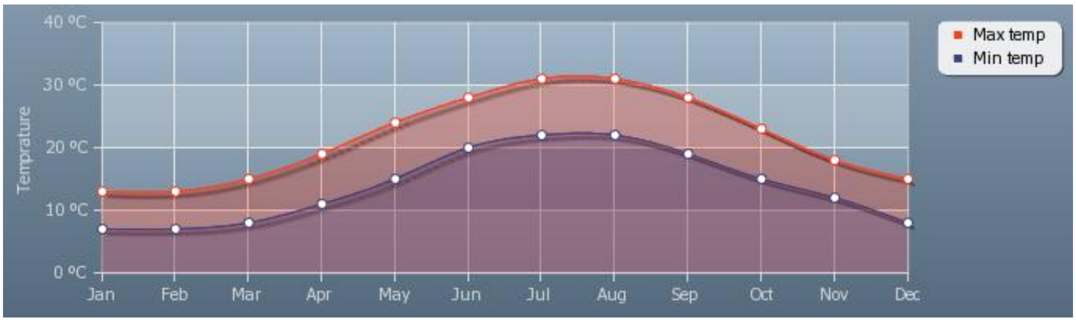
Table 4.8.1.1: Annual Oil Consumption, Total CO_2 Emission and Total CO_2 Saving Potential of Solar Heating, Residential Sector – Space Heating, Greece
Source: Author

Residential Sector – Space Heating	
Annual Oil Consumption	1.913.764 t_{oil}/a
Total CO_2 Emission	2.685.654 tCO_2/a
Total CO_2 Saving Potential	805.696 tCO_2/a

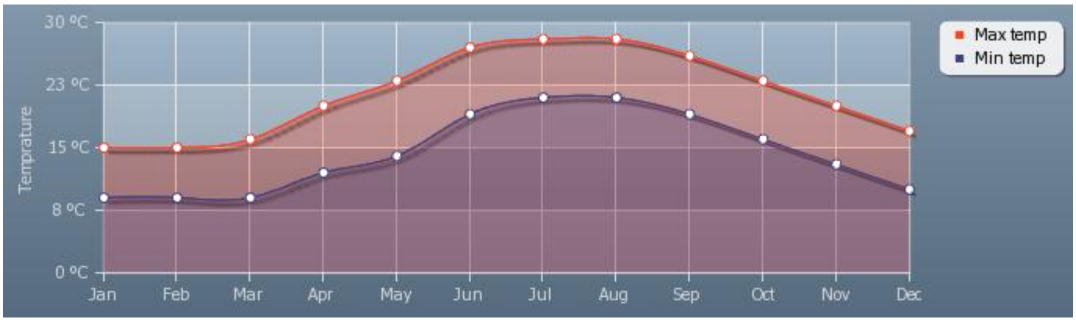
Figure 4.8.1.2: Map of Greece
Source: amerispan.com



Thessaloniki



Athens



Crete

Figure 4.8.1.3: Average Maximum and Minimum Temperatures of Thessaloniki, Athens and Crete in Greece
Source: World Weather and Climate Information, 2009

4.8.2 Cooling Case – Residential Buildings

The purpose of Figure 4.8.2.1 is to show the apparent seasonal electricity consumption of a city in Greece, Athens. Electricity load peaks twice a year, in both winter and summer months. Electricity demand depends on a variety of circumstance including the type of appliance used as well as the trigger point (i.e. choice to utilize) of equipment initiation. The option to start operation is based on several factors, which need to be taken into consideration, as solely indoor temperature is not sufficient to determine electricity consumption of air conditioning. Among others, behaviour patterns depend on the price of energy related to income, as well as consumer preferences (Psiloglou et al., 2009).

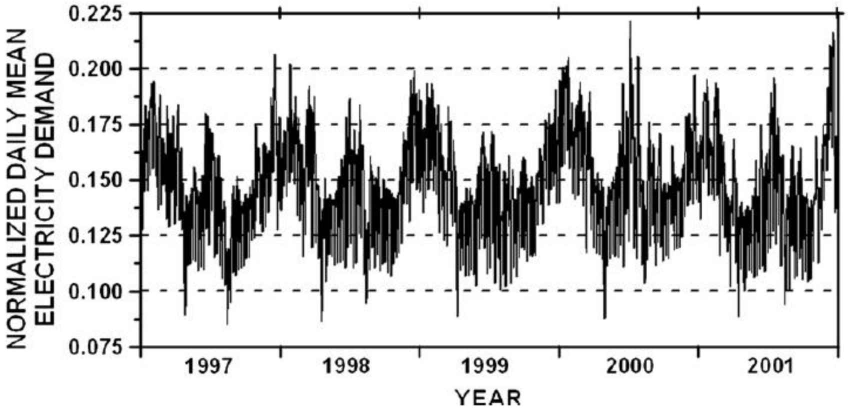


Figure 4.8.2.1: Daily Mean Electricity Demand, Athens, Greece
Source: Psiloglou et al., 2009

Greece's electricity consumption in 2011 accounted for around 58 billion kWh (CIA- The World Factbook – also see Figure 4.7.1); this corresponds to about 58 TWh. According to the Environmental Change Institute of the University of Oxford, in 1998, 30% of Greek's total electricity consumption was devoted to the residential sector. Even though Greek electricity generation increased significantly by 70% between the years 1996 and 2010 (University of Oxford), for the sake of this paper's case study it will be assumed that the 30% share of electricity demand of households has remained constant until today, meaning this would account for a yearly electricity consumption of 17.4 TWh by the residential sector. The following calculations and assumptions are made to reach a result about yearly energy consumption by air conditioning alone in the residential sector in Greece, to further estimate yearly CO_2 discharge into the atmosphere.

In Athens, “the percentage of households with at least one installed air conditioner varies from 48% to 69% for the lower and upper income classes respectively” (Santamouris et al., 2006). Referring to this citation and bearing in mind the current proportionality between economic wealth and resource consumption, Greece would experience a significant increase in CO_2 emissions as fuel poverty decreases and the economic standard per capita increases. Thus, an early stage of decoupling, by means of renewable energy as an alternative fuel source to fossil fuels, would potentially contribute to resolving the issue.

Out of the 4.906.200 dwelling units in Greece which was assumed to afford space heating and cooling, the subsequent calculations will make the two different assumptions that 48% and 69% of all dwelling units in Greece to have one electrically driven packed air conditioning unit installed. Assuming that every air conditioner will be operated once the indoors temperature reaches 25°C, then according to Figure 4.8.1.2, which represents the northern, central and southern part of Greece, this cooling appliance will be activated for an average of five months (May until September, i.e. 153 days). Further assuming 2000 Watt air conditioners will operate six hours each for of this period, this would amount to a daily electricity consumption of 12 kWh per dwelling unit, accounting to an annual consumption of 1836 kWh.

If 48% of all dwelling units (2.380.538 homes) cool their residence, then a yearly electricity consumption of 4.371.325.056 kWh/a, that is to say, about 4.4 TWh/a, is to be expected. However, if 69% of dwelling units operate an air conditioner, then 6.283.779.768 kWh/a, i.e. 6.3 TWh/a, of electricity will be consumed by the residential sector for space cooling purposes in Greece. This amounts to around 25-36% of total electricity consumption (17.4 TWh in 2011) by Greek residential buildings for cooling purposes.

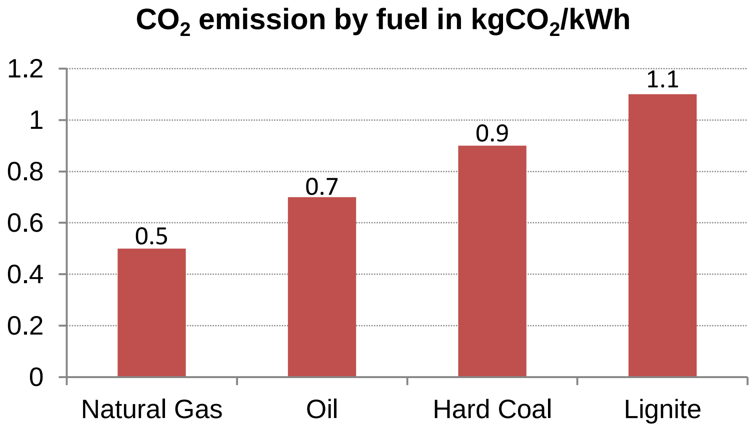


Figure 4.8.2.2: CO_2 Emission by Fuel, $kgCO_2$/kWh
Source: Buhagiar, 2008

Figure 4.8.2.2, illustrates CO_2 emissions in kg from different fuel sources per kWh of electricity generation. According to the World Bank report of 2011, sources of electricity are as follows: coal is the principle source of fuel, contributing the highest share of 45.1%, next in line are natural gas, oil and the hydroelectric sources, representing 27.2%, 12.6% and 10.9% respectively, while the rest (4.2%) of electricity is produced otherwise. Assuming that the 4.2% is generated from renewable energy sources (RES) other than hydropower, then an aggregate of 15.1% of electricity is produced by RES in Greece (18% RES by 2020 is Greece's target). Abstracting 15.1% of 4.4 TWh/a and 6.3 TWh/a (respectively, 48% and 69% of dwelling units with one air conditioner installed), would result in an annual electricity consumption of about 3.7 – 5.3 TWh/a by means of fossil fuel combustion for space cooling of the Greek residential sector. Table 4.8.2.1 illustrates the electricity consumption of the residential sector in Greece, with respect to the different shares of fossil fuel sources for electricity generation, revealing an annual electricity consumption by Greek residential buildings of 3.2 – 4.5 TWh/a. With respect to Figure 4.8.2.2, Table 4.8.2.2 represents relative CO_2 emissions (in kg) by the residential sector in Greece, distinguishing between the diverse fossil fuel sources of electricity generation. In total, 2.676.365 – 3.847.255 tCO_2 is discharged into the atmosphere on a yearly basis.

To conclude, if solar thermal installations for solar cooling purposes for the residential sector of Greece were to be implemented on 30% of dwelling units, an annual saving of CO_2 emissions of 802.910 tCO_2 to 1.154.168 tCO_2 can potentially be reached (see Table 4.8.2.3).

Table 4.8.2.1: Annual Electricity Consumption for Space Cooling, Residential Sector, Greece
Source: Author

Fossil Fuel as Electricity Source	48% of dwelling units with one installed air conditioner	69% of dwelling units with one installed air conditioner
Coal (45.1%)	1.675.747.460 kWh/a 1.7 TWh/a	2.408.886.974 kWh/a 2.4 TWh/a
Natural Gas (27.2%)	1.010.650.353 kWh/a 1.0 TWh/a	1.452.809.882 kWh/a 1.5 TWh/a
Oil (12.6%)	468.168.914 kWh/a 0.5 TWh/a	672.992.813 kWh/a 0.7 TWh/a
Total Electricity Consumption	**3.154.566.727 kWh/a** **3.2 TWh/a**	**4.534.689.669 kWh/a** **4.5 TWh/a**

Table 4.8.2.2: Annual CO_2 Emissions in kg from Space Cooling, Residential Sector, Greece
Source: Author

Fossil Fuel as Electricity Source	CO_2 emission from 48% of dwelling units with one installed air conditioner [tCO_2/a]	CO_2 emission from 69% of dwelling units with one installed air conditioner [tCO_2/a]
Coal (1.1kgCO_2/kWh)	1.843.322	2.649.775
Natural Gas (0.5kgCO_2/kWh)	505.325	726.405
Oil (0.7kgCO_2/kWh)	327.718	471.045
Total CO_2 Emission	**2.676.365**	**3.847.225**

Table 4.8.2.3: Annual Saving Potential of CO_2 Emissions in kg from Space Cooling, Residential Sector, Greece
Source: Author

Fossil Fuel as Electricity Source	CO_2 saving potential from 48% of dwelling units with one installed air conditioner [tCO2/a]	CO_2 saving potential from 69% of dwelling units with one installed air conditioner [tCO2/a]
Coal	552.997	794.932
Natural Gas	151.598	217.922
Oil	98.315	141.314
Total Saving Potential	**802.91**	**1.154.168**

4.8.3 Cooling Case - Non-Residential Buildings

Greece's electricity consumption in 2009 amounted to around 62 billion kWh (World Bank, 2010); this corresponds to 62 TWh. As stated in Chapter 4.7 of this paper, in 2003, 2.9 TWh was solely consumed by central air conditioning systems in Greece, which accounts for approximately 4.7% of Greek final electricity consumption. For the sake of this case study, we suppose that central air conditioning systems are installed for all non-residential buildings in the country. Assuming a 3500 Watt central air conditioning system is installed with an operation of six hours per day from May to September (i.e. 153 days a year) then a daily electricity consumption of 21 kWh is to be expected, accounting for 3213 kWh/a. Following Table 4.8.1, Greece has 4.315.000 existing buildings, of which 23% are of non-residential use. This would amount to 992.450 buildings, yearly consuming 3.188.741.850 kWh/a, a significant 3.2 TWh/a. However, assuming that 15.1% of electricity is supplied by renewable energy sources, non-residential buildings in Greece consume 2.707.241.831 kWh/a from fossil fuel combustion. With respect to the diversity of fossil fuel sources regarding electricity generation, Table 4.8.3.1 represents annual electricity consumption by fuel source. Table 4.8.3.2 shows annual CO_2 emissions from non-residential buildings, differentiating between fossil fuel sources, revealing a total annual CO_2 emission of 2.296.881 tCO_2/a. Thus, 689.065 tCO_2 emissions may be eliminated if 30% of non-residential buildings in Greece would adopt solar thermal technologies for space cooling purposes.

Table 4.8.3.1: Annual Electricity Consumption of Space Cooling, Non-Residential Sector, Greece
Source: Author

Fossil Fuel as Electricity Source	**Electricity Consumption of Space Cooling of Non-Residential Buildings**
Coal (45.1%)	1.438.122.574 kWh/a 1.4 TWh/a
Natural Gas (27.2%)	867.337.783 kWh/a 0.9 TWh/a
Oil (12.6%)	401.781.473 kWh/a 0.4 TWh/a
Total Electricity Consumption	**2.707.241.830 kWh/a** **2.7 TWh/a**

Table 4.8.3.2: Annual CO_2 Emissions in kg from Space Cooling, Non-Residential Sector, Greece
Source: Author

Fossil Fuel as Electricity Source	CO_2 emission from Space Cooling of Non-Residential Buildings [tCO_2/a]
Lignite ($1.1kgCO_2/kWh$)	1.581.935
Natural Gas ($0.5kgCO_2/kWh$)	433.669
Oil ($0.7kgCO_2/kWh$)	281.247
Total CO_2 Emission	**2.296.881**

Table 4.8.3.3: Annual Saving Potential of CO_2 Emissions in kg from Solar Space Cooling, Non-Residential Sector, Greece
Source: Author

Fossil Fuel as Electricity Source	CO_2 saving potential of Non-Residential Buildings from Solar Space Cooling [tCO2/a]
Coal	474.581
Natural Gas	130.11
Oil	84.374
Total Saving Potential	**689.065**

4.9 Overview of installed solar cooling and heating systems in Greece

A technical report was published in 2009 by the International Energy Agency under Task 38 of "Solar Air-Conditioning and Refrigeration" regarding the "state of the art on existing solar heating and cooling systems". The current market offers different types of thermally driven chillers as well as a variety of solar thermal technologies. Thus, with the help of this report, the aim of the following text is to aid in the proper selection of technology with respect to location of application and end use of small scale solar heating and cooling installations. Globally, 163 small scale installations have been implemented, out of which 38% are for office buildings, 28% serve private households, 8% for industries, 7% serve education centres such as schools, universities and kindergartens (IEA, 2009). This sums up to 81%, with the rest of the applications installed at sport centres, laboratories and others. Regarding these small scale installations, 90% utilize absorption chillers and 10% install adsorption chillers

(IEA, 2009). Desiccant cooling systems, whether solid or liquid sorbent phases, are only used, according to this study, within large scale systems, where only two liquid desiccant cooling systems are known, one in Germany and the other in China. In Greece, the distribution of cooling power assisted by thermally driven chillers is as follows: absorption chillers provide roughly 450kW, while adsorption chillers provide around 700kW (IEA, 2009).

With regard to solar collectors, the most common technologies are flat-plate and evacuated tube collectors. Greece has an installed surface area of solar collectors of about 3800m² by flat-plate collectors and 400m² are covered by evacuated tube collectors (IEA, 2009). Due to the intermittent nature of solar energy applications, backup systems have to be taken in consideration. According to this study, 43% of solar thermal installations include a fossil fuel boiler, 21% use a cogeneration unit, a further 21% backup their system with district heating, while the remaining 15% install heat pumps.

Table 4.7.1 refers to the costs (in USD) and relevant characteristics of solar thermal system installation for a single-family dwelling and multi-family dwelling in OECD countries in Europe (thus, referable to Greece) in the year 2007. These costs exclude the price of the cooling device to provide air conditioning. According to the German Company, Solar Next, and after the personal telephone conversation for the sake of this thesis, it was revealed that typical prices for an 8kW and 15kW cooling machine is around 20.000 to 45.000 Euros per device.

Table 4.7.1: Costs and Characteristics of Solar Thermal System for Single- and Multi-Family Dwellings in OECD Countries in Europe in 2007
Source: IEA, 2010

	Single-family dwelling	**Multi-family dwelling**
Typical size: water heating (kW_{th})	2.8 - 4.2	35
Useful energy: water heating (GJ/system/year)	4.8 - 8	60 - 77
Useful energy: space and water heating (GJ/system/year)	16.1 - 18.5	134 - 230
Installed cost: new building (USD/kW_{th})	1.140 - 1.340	950 - 1.050
Installed cost: retrofit (USD/kW_{th})	1.520 - 1.730	1.140 - 1.340

4.10 Best Practice Example – Greece – Commercial: Hotel

Figure 4.10.1 Source: www.raee.org

The “Rethimno Village” is a hotel situated in Crete, in southern Greece and was the first hotel worldwide to use solar cooling. The solar thermal installation implemented provides space cooling and heating in addition to the provision of hot water for the heating of the swimming pool. Since 11 September 2000, 448m² of selective surfaces have been fitted with flat plate collectors (Figure 4.10.1) to supply space heating and cooling for a total area of 3.000m². Further, 199m² of polypropylene collectors (Figure 4.10.3) were installed for heating the swimming pool (Figure 4.10.4). Thus, a total of 647m² of roof surface was utilized for the solar thermal collectors of SOLE Climasol. Equipped with adsorption cooling technology (Figure 4.10.5) of 105kW power, Rethymno Village offers a bed capacity of 170 beds. SOLE S.A. was responsible for the design, supply as well as the installation of the system.

Driving temperature of 70-75°C operates the adsorption chiller with a COP of 60%, producing cool water of 8-10°C. In winter, the solar collectors produce hot water of 55°C and then circulate around the buildings to the installed fan coil units. In case of unfavourable weather conditions or during lack of solar radiation (e.g. at night), a substitution to a gas boiler with a capacity of 600kW is made.

The hotel’s yearly demand of total energy load is 1.498.249 kWh, out of which 650.743 kWh is provided annually, representing a 43% solar coverage, which can be regarded as the primary energy saving, due to the utilization of free solar energy. Furthermore, total investment costs amounted to 264.123 euro, while 50% was subsidized by the National Operational Programme for Energy of the Greek Ministry of Development.

Table 4.10.1, shows the emissions reduction due to the solar thermal installation of the hotel. Figure 4.10.2 demonstrates the general plan of the system.

Table 4.10.1: Emission Reduction: Solar Thermal Installation at Rethimno Village Hotel in Crete, Greece

Emissions [kg/year]	
CO_2	187
SO_2	17.919
NO_x	1.463
HC	53
Particulates	923

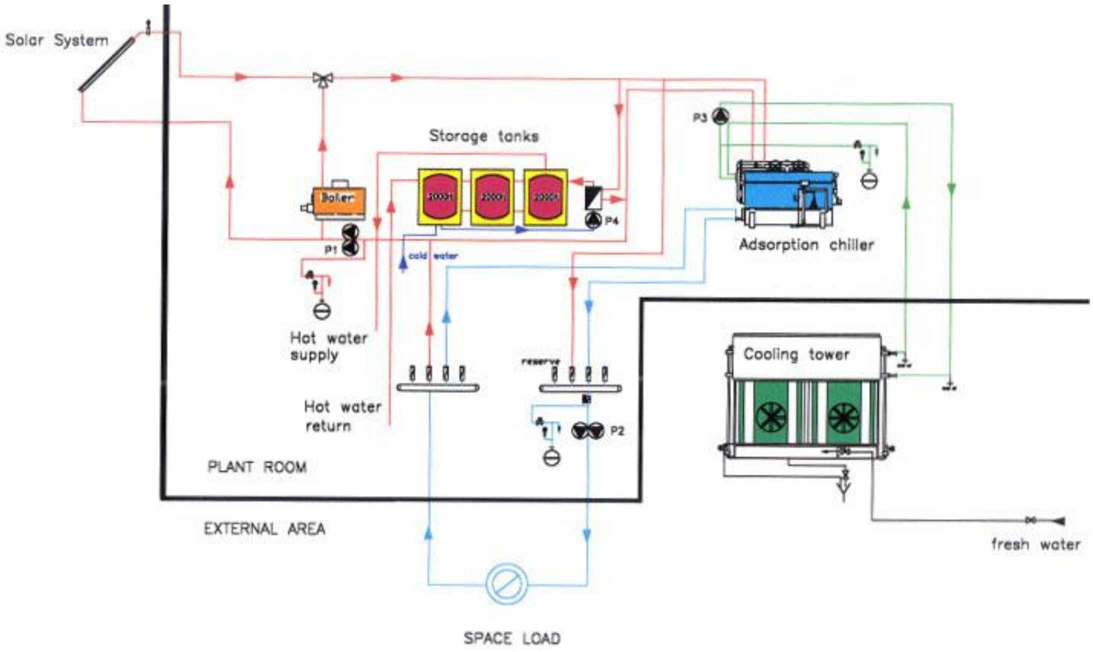


Figure 4.10.2: General Plan of Solar Thermal Installation at Rethimno Village Hotel in Crete, Greece

Figure 4.10.3
Source: www.ree.org

Figure 4.10.4
Source: www.utazz.com

Figure 4.10.5
www.raee.org

4.11 Best Practice – Greece – Residential

Solar Air Conditioning in Europe (SACE) was a European Union project of Research and Development, which ended in August 2003 after the duration of 18 months, to produce a “comprehensive and comparative study in solar air conditioning in Europe” (SOLAIR homepage). One of the case studies took place in Athens, Greece, of a residential building, with an air conditioned floor area of 150m². A single-effect absorption chiller with a capacity of 10kW, utilizing water-lithium bromide as working pairs (refrigerant-absorber), was manufactured to be tested for this project explicitly for floor cooling and design optimization. The status of the project is, therefore, a pilot production. The prototype absorption chiller has a COP of 65%, which required a driving temperature of about 77°C. It was, thus, possible to install 37m² of flat plate collectors, which produced hot water of 80-90°C. For the purpose of heating, radiant floors require a hot water supply of 30 to 60°C, while cooling operates at 7 to 24°C. Figure 4.11.1 demonstrates the system plan.

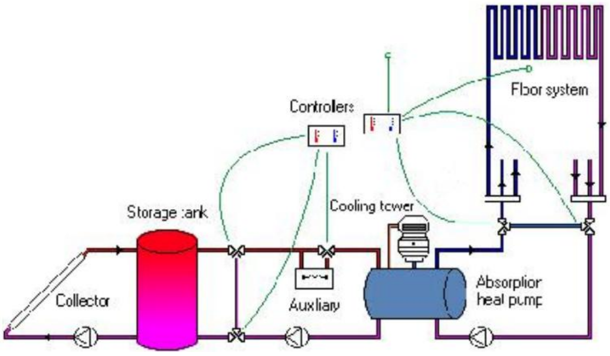


Figure 4.11.1: Schematic of System Plan for Solar Thermal Installation in a Residential Building
Source: SACE, 2000

An electric heater was installed within the system as a backup, with a heater capacity of 13.7 kW. Further, total investment costs amounted to 20.525 Euros. A 20-27% energy saving was observed, compared to conventional cooling devices which utilize electrically driven mechanical compressors. A 5-9 year payback time is estimated if solar collectors drive the absorption chiller and 6.5-14 years for the complete system of installations (e.g. heat storage, backup system, etc.), when compared to the conventional electrical approach of cooling.

5. Results and Discussion

With regard to Greece and the case study of this thesis, it was essential to go into details concerning energy consumption for heating and cooling purposes for buildings so as to identify the extent of its environmental impact with respect to CO_2 emissions in order to further consider whether the heating and cooling sector is a potential niche where clean and renewable solar thermal energy may be used as an alternative source to replace traditional source of energy so as to mitigate emissions.

Greece's gross inland energy consumption originates from 93% of CO_2 emitting fuel sources. The country's indigenous energy resources are substantially limited to coal, primarily lignite, which had the most significant share of 81% in total primary energy production in 2009 (Eurostat, 2011). In 2010, lignite production amounted to 56.5 million tonnes, from which 27.4 TWh were produced, out of the country's total power generation of 47.9 TWh. This means that 75% of total power generation came from Greek lignite-fuelled thermal power stations (EURACOAL). Compared to other fossil fuels, lignite is the least environmentally friendly source, as it emits 1.1 $kgCO_2/kWh$, while hard coal, oil and natural gas, respectively, discharge 0.9, 0.7 and 0.5 $kgCO_2/kWh$ (Buhagiar, 2008).

Remarkable is the high ratio of residential compared to non-residential buildings, as 77% out of all buildings in Greece are for residential use (Pomonis, 2011). It is reported that there are 6.630.000 dwelling units. However, 26% of households in Greece suffer from fuel poverty (Pomonis, 2011), which is incorporated in the calculations for this case study to enable more accuracy. Therefore, regarding the number of residential housing units in Greece, it will be assumed that 4.906.200 units can afford basic energy needs for heating and cooling.

Today in Greece, space cooling by means of air conditioning "is exclusively based in the use of electric energy" (Koroneos et al., 2009), whereas the most common "heating system in Greek buildings is a central oil-fired boiler, distributing the heat produced to hydronic radiators" (Papadopoulos et al., 2008). For this reason, the case study assumes that, for the purpose of heating and cooling of all Greek buildings, only oil and electricity, respectively, are consumed.

5.1 Results of Heating Case: Residential Buildings

The Greek residential sector consumes around 15% of total oil consumption in the country (IEA, 2010), of which 69% is the demand for space heating (Centre for Renewable Energy Source and Saving (CRES), 2009). Yearly, almost 2 million tons of oil are required for space heating alone, which is responsible for around 17 million kgCO_2 emission per day from the 5 million dwelling units, each accounting for 3.4 kgCO_2 per day. The case study of this thesis distinguishes between three climatic zones in Greece, differentiating their heating behaviour according to outdoor temperatures during winter time. Further, this case study selects the cities of Thessaloniki, Athens and Crete to represent the whole of Greece according to the three climatic zones of North, Central and South Greece, respectively. According to the average maximum temperatures of these representative cities, it was calculated that average heating days of Greece's residential buildings amounted to 161 days per year, emitting approximately 2.7 million tonnes of CO_2, on an annual basis, into the atmosphere.

If solar thermal technologies were to be implemented on 30% of Greek dwellings, for space heating, a yearly saving potential of CO_2 emission would amount to 805.696tCO_2.

5.2 Results of Cooling Case: Residential and Non-Residential Buildings

Greece yearly consumes around 58 TWh of electricity (CIA – The World Factbook, 2011), of which 30%, i.e. 17.4 TWh, is devoted to the residential sector (University of Oxford). In Athens, 48% to 69% of households have at least one installed electrical air conditioner (Santamouris et al., 2006). This case study assumes that these percentages (48% and 69%) apply for the whole of Greece, thus two separate results were obtained. Additionally, it is assumed that 2000 Watt air conditioners are operated for an average of 153 days annually, for six hours every day, amounting to an annual consumption of 1836 kWh per dwelling unit. According to the calculations of the case study, around 25-36% of total electricity consumption for Greek residential buildings is required to supply cooling.

According to the World Bank report of 2011, sources of electricity are as follows: coal is the principle source of fuel, contributing the highest share of 45.1%, next in line are natural gas, oil and the hydroelectric sources, representing 27.2%, 12.6% and 10.9% respectively, while the rest (4.2%) of electricity is produced otherwise. This thesis assumes that the latter 4.2% of electricity is produced by other renewable energy sources. Thus, about 85% of Greek electricity production emits CO_2, which according to computations of the case study, results in an annual electricity consumption of about 3.2 – 4.5 TWh/a by means of fossil fuel combustion for space cooling of the Greek residential sector. This leads to an estimation of CO_2 emission of 2.7 – 3.9 million tonnes into the atmosphere on a yearly basis.

Therefore, if solar thermal installations for solar cooling purposes for the residential sector of Greece were to be implemented on 30% of dwelling units, an annual saving of CO_2 emissions of 802.910 tCO_2 to 1.154.168 tCO_2 can potentially be reached.

Similar calculations and assumptions have been undertaken for non-residential buildings regarding cooling purposes. With the estimated electricity consumption of 2.9 TWh for central air conditioning (Koroneos et al., 2009) and further assumptions of 3500 Watt system of an operation of six hours and 153 days a year, non-residential buildings are responsible for a total CO_2 emission 2.3 million tonnes annually.

Thus, 689.065 tCO_2 emissions may be eliminated if 30% of non-residential buildings in Greece would adopt solar thermal technologies for space cooling purposes.

5.3 Resume

In Greece, a packed air conditioning unit, which evidently is associated with high energy demand and greenhouse gas emissions, is most common in residential buildings as well as in many tertiary buildings (Argiriou and Mirasgedis, 2003). Furthermore, in summertime, Greece’s electricity demand rises due to cooling needs, as utilization of cooling, ventilation and air conditioning systems increases dramatically (Koroneos et al., 2009), leading to an electricity supply dilemma (Giakoumi and Latridis, 2009). Further, it should be born in mind that 85% of Greek electricity production emits CO_2 (World Bank report, 2011).

When reviewing Greece's gross inland energy consumption, it is oil that dominates as an energy source, not native lignite. The country is dependent by 99.7% on oil imports, according to 2009 data (EIA, 2010). Total energy consumption in 2009 amounted to 30.629 ktoe, out of which 55% was oil (Eurostat, 2009).

The climate of Greece favours the application of solar energy, as it is a Mediterranean climate with long, dry and warm summers and "many hours of sunshine almost all year", while winter is short, mild and rainy (EEA, 2010). Thus, given that Greece's heating and cooling sector significantly depends on the combustion of fossil fuels, the use of renewable energy sources as alternative clean energy with the aim of mitigation of CO_2 emission demonstrate a high implementation potential in the household sector.

If solar heating and cooling is applied on 30% of the residential sector of Greece, a total annual CO_2 saving potential of an average of 1.8 million tonnes of carbon dioxide emission may be achieved.

Table 4.1 recapitulates current CO_2 emissions of the Greek building sector as well as the potential CO_2 emission reduction (30% application of solar thermal systems), according to the case study of this thesis, therefore, verifies the hypothesis, which *states that the replacement of traditional energy source of fossil fuel combustion by the input of solar energy in the housing sector can contribute remarkably to carbon dioxide mitigation.*

Table 4.1: Current CO_2 Emissions of Greek Building Sector and Potential Emission Reduction
Source: Author

[tCO_2/a]	**Space Cooling**	**Space Heating**	
	Residential Buildings	**Residential Buildings**	**Non-Residential Buildings**
Total CO_2 Emissions	3.261.795	2.296.881	2.685.645
Total CO_2 Saving Potential	978.538	689.065	805.696

5.4 Economic Aspects

A multi-family dwelling would spends between 766 and 845 Euros on installation costs for a solar thermal system, excluding the cooling device, if applied to a new building, and 919 to 1081 Euros to retrofit (EIA, 2010). Costs may reach up to 1395 Euros, if implementation is intended on a single-family dwelling (EIA, 2010). Assuming a further 2000 Euros investment, for the cooling device per dwelling, needs to be taken into consideration (personal conversation with German Company, Solar Next).

Thus, a maximum spending of 15.4 - 17 billion Euro is required if all 5 million dwelling units are to be fitted with solar thermal installations for residential heating and cooling.

Greece’s residential sector annually consumes an average of 3.85 TWh (3.850.000.000 kWh/a) of electricity for air conditioning. An amount of 0.13 Euro is charged per kWh of consumption (IEA, 2011), which leads to a yearly payment of 500 million Euros. For space heating, the residential sector consumes 2 million tonnes of oil annually, for which, 0.73 Euros is charged per litre (IEA, 2011). This amounts to an annual expense of 1.5 billion Euros.

Financial payments for space heating and cooling of Greece’s residential sector amount to an annual sum of 2 billion Euros. Therefore, payback period is estimated at roughly 7.7 to 8.5 years.

6. Conclusion

This master’s thesis selects a Southern Mediterranean European country, Greece, because the climatic conditions of the country are favourable to the provision of *solar heating and cooling* for the building sector. The objective is to identify Greece’s potential contribution to *climate change abatement* through the utilization of the environmentally sound technologies of *solar thermal energy*. In order to define the current *carbon footprint* of heating and cooling for the Greek building sector , an in-depth analysis of *energy consumption* behaviour patterns is presented throughout this paper, in addition to a specific case study, which required the use of assumptions, estimates and approximations, to finally achieve the results described in the text below.

Today, *93%* of Greek energy production originates from *fossil fuels* (EIA, 2011), which are carbon dioxide emitting sources, thus, potentially contributing to a negative impact on the environment and, consequently, global climate change. However, the energy consumption required to supply, amongst others, space heating and cooling of buildings, is unavoidable.

According to the case study of this thesis, *space heating* of the *5 million dwelling units* of Greece’s residential sector consumes annually around *2 million tonnes of oil*, which is responsible for a discharge of an estimated *2.7 million tonnes of carbon dioxide* into the atmosphere, on an annual basis.

Further, the case study identified a yearly electricity consumption of *3.2 to 4.5 TWh*, for *space cooling* of the Greek’s residential sector, whereas *2.7 TWh* of electricity is supplied to non-residential buildings for the same purpose. This leads to an aggregate annual carbon dioxide emission of between *2.7 and 3.8 million tonnes of carbon dioxide* by the residential sector, in addition to a total of *2.3 million tonnes of carbon dioxide* release into the environment by non-residential buildings.

Therefore, space heating and cooling for the Greek building sector is accountable for the yearly emission of an average of ***8.3 million tonnes of carbon dioxide*** into the environment, through fossil fuel combustion, to satisfy energy demand.

Installation of solar thermal space heating and cooling on 30% of Greek's building sector potentially saves an average of *2.5 million tonnes of carbon dioxide* annual discharge into the environment.

According to the *European Union Allowance* (EUA) contract of 4 May 2012, an amount of *9 Euros* was traded per tonne of carbon dioxide saving (Reuters, 2012). Thus, Greece has the potential of contributing to the global challenge of climate change abatement and, further, generating national revenues of roughly *22 million Euros* per annum, if 30% of Greek buildings apply solar space cooling and heating by solar thermal energy, through an approach of a carbon trading project.

Apart from the contributing to climate change abatement, Greek revenues through carbon trading, may reach almost 75 million Euros yearly if the entire Greek building sector implements the environmentally sound and renewable energy source of solar thermal space heating and cooling.

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